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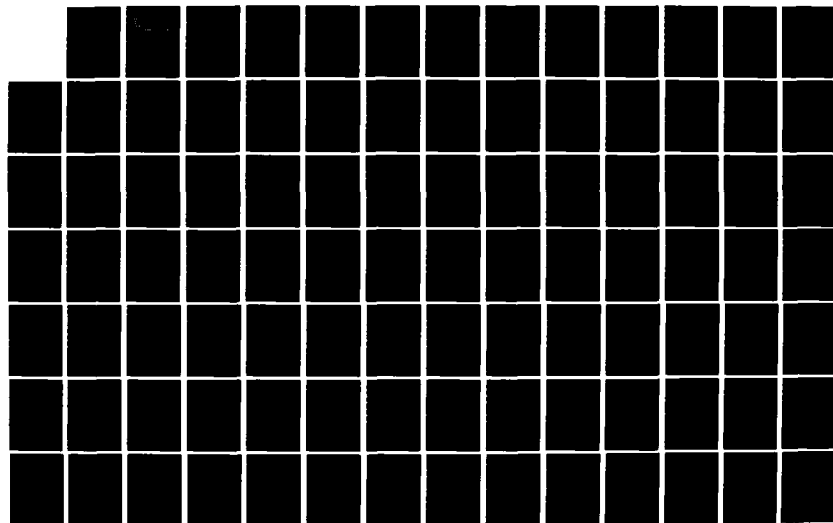
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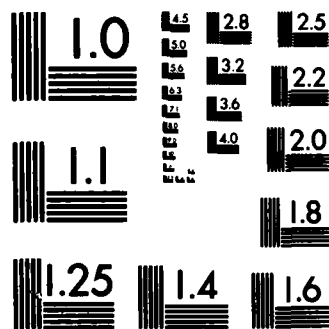
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OPTICAL FLOW AND TEXTURE VARIABLES  
USEFUL IN SIMULATING SELF MOTION (II)

Dean H. Owen  
Department of Psychology

For the Period  
February 1, 1982 - March 31, 1983

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH  
Directorate of Life Sciences  
Bolling Air Force Base, D.C. 20332

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## 20. Abstract, continued

linkages are discussed, and several solutions are suggested. A case is made for the necessity of considering the entire perception-(control) action cycle in the study of self-motion sensitivity, and implications of ecological optics experiments for the understanding of "smart" information-specifying visual system mechanisms are discussed.

Three experiments are presented testing the usefulness of optical variables and invariants for detecting changes in speed and altitude. Several event-duration variables were also explored. Seven main points of interest are indicated by the results: (1) Eyeheight-scaled visual information about loss in altitude is much more perceptually effective than ground-texture-scaled information. The results suggests that future research should concentrate on the eyeheight metric, both in the study of "smart" perceptual mechanisms underlying self-motion sensitivity and in the study of procedures for training pilots to attend to the most salient sources of information. (2) Optical flow acceleration, long touted as important information for approach to a surface, had essentially no utility under the conditions of one experiment and proved to be detrimental under the conditions of a second study. This result is relevant to the differences in optical information during fixed-wing versus rotary-wing or V/STOL approaches to or avoidance of the ground. (3) Of the three candidates tested, optical (perspectival) splay was the most effective specifier of fractional loss in altitude, which is the higher-order variable to which observers are most sensitive. Future research should test for splay sensitivity under more ecologically valid ground-texture conditions. (4) Sensitivity to information specifying loss in altitude became increasingly poorer as optical flow rate increased, particularly for small values of fractional loss in altitude. This result has critical implications for low-level, nap-of-the-earth flight where flow rates are highest and where fractional loss is low due to either low sink rates or to small upslopes in the ground surface. (5) A preview duration of five seconds before a change in heading or speed resulted in great improvement in ability to detect the change. Since this result is relevant to cloud break-out and looking up from instruments and controls, further research should focus on optimizing this effect and exploring its relationships to the potentially negative effects of adaptation to flow-pattern variables. (6) Surprisingly, event durations as brief as two seconds had little effect on sensitivity to loss in altitude, even though surreptitiously recorded reaction times correlate highly with accuracy. (7) Optical density had little effect in any experiment, suggesting that fine surface texture detail contributes little to the simulation and perception of change in self motion.

Our findings to date provide a basis for the development of tests to evaluate candidates for flight training, the simulators with which pilots are trained, and improvement in sensitivity with training. In addition, our approach provides a sound empirical foundation from which to begin interactive experiments in which pilots control, rather than simply react to, the variables and invariants of optical stimulation.

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Final Technical Report  
June, 1983

OPTICAL FLOW AND TEXTURE VARIABLES  
USEFUL IN SIMULATING SELF MOTION (II)

THE OHIO STATE UNIVERSITY  
COLUMBUS, OH 43210

Dr. Dean H. Owen

Controlling Office: USAF Office of Scientific Research/NL  
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## ABSTRACT

This report outlines a program of research applying ecological optics to the study of visual information useful for detecting and guiding self motion during flight. Techniques are presented for isolating optical sources of information by controlling simulated flight path and speed variables in conjunction with ground surface texture variables. Problems encountered in the design of experiments using higher-order ratios exhibiting constrained linkages are discussed, and several solutions are suggested.

Three experiments are presented testing the usefulness of optical variables and invariants for detecting changes in speed and altitude. Several event-duration variables were also explored. Seven main points of interest are indicated by the results: (1) Eyeheight-scaled visual information about loss in altitude is much more perceptually effective than ground-texture-scaled information. The results suggests that future research should concentrate on the eyeheight metric, both in the study of "smart" perceptual mechanisms underlying self-motion sensitivity and in the study of procedures for training pilots to attend to the most salient sources of information. (2) Optical flow acceleration, long touted as important information for approach to a surface, had essentially no utility under the conditions of one experiment and proved to be detrimental under the conditions of a second study. This result is relevant to the differences in optical information during fixed-wing versus rotary-wing or V/STOL approaches to or avoidance of the ground. (3) Of the three candidates tested, optical (perspectival) splay was the

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## INTRODUCTION

OPTICAL FLOW AND TEXTURE VARIABLES USEFUL IN  
SIMULATING SELF MOTION II

Dean H. Owen

The Ohio State University

As the final report of a two-year project, we present three experiments conducted since the interim report (Owen, 1982). In addition, the report summarizes the approach we have pursued over the past four years, by outlining the assumptions made, the problems encountered in isolating optical variables, and some possible solutions we are exploring. Implications are discussed both for the perceptual system mechanisms responsible for sensitivity to visual self-motion information and for application of the tests we have developed to problems of pilot and simulator evaluation. Implications of our approach and results for problems encountered during low-level, high-speed flight and during landing are also discussed.

The Approach

Our research is based on the ecological framework for the study of self-motion perception developed by James J. Gibson. His first experiment on the visual information for detecting the point of impact during a landing approach (Gibson, 1947) led to the first mathematical optical flow analysis (Gibson, Olum, & Rosenblatt, 1955). Further theoretical developments eventually culminated in a descriptive account of how an individual controls optical stimulation in order to achieve desired locomotion through his environment (Gibson, 1979). Our program continues the quantitative exploration of ecological optics, with an emphasis

on empirical tests of the usefulness of optical information in detecting and guiding self motion during flight.

The research conducted was predicated on the assumption that the role of visual perception in flight simulation can be understood only by considering the entire perception-action cycle involved in flight. As such, it represents the beginning of an attempt to move from traditional stimulus-response procedures to a paradigm which mimics the natural perception-action cycle in order to discover the information a pilot uses in detecting and guiding his own movement through the environment.

The cycle consists of the following four phases: (1) A source of radiation is required which either illuminates other surfaces or is itself a luminous surface. In actual flight, the sun or artificial lighting illuminates ground surfaces, or, at night, the texture elements on the ground may themselves be luminous. (2) Surface texture discontinuities, which result from differences in pigmentation or in luminosity characteristics, are necessary. These differences specify the edges, intersections, facets, and elements of the textured surfaces of the environment. Whether the surfaces reflect light or are luminous, they provide (3) structured arrays of light to places in the environment which can potentially be occupied by an eye. The optical discontinuities available at potential places of observation are specific to, and hence potentially informative about, surface texture discontinuities. When an eye is moved along a path of observation, it can continuously sample change and nonchange in the optic-array structure at different places along the path. These optical transformations are specific to, and thus

informative about, the path, direction of movement, and speed of the eye. (In the special case of visual perception mediated by a display such as that used in a flight simulator, the display mimics reflected light at a cross section of the ambient optic array. The eye does not move translationally, but the display transforms the optic array in ways appropriate for translation and rotational motions.) (4) An individual capable of visually perceiving and guiding locomotion can be simplified for the present purpose into three subsystems: (a) a sentient system sensitive to optical discontinuities, (b) an inter-linking nervous system, and (c) an action system. (For the special case of manned flight, characteristics of the action system itself can be essentially disregarded, since locomotion is mediated by hardware which is controlled by the individual. The distal consequences of control actions (changes in path, direction, and speed) and the optical consequences of these adjustments (transformations in the optic array specific to the control actions) are, however, of critical importance.) Since actions produce visually perceptible changes in the structure of the light, the transformations can serve as feedback for the pilot to assess whether the intended optical conditions were achieved. This brings us back to the phase which deals with optic array information. The pilot will continue to loop through the perception-action cycle until the flight task is completed or until a critical error is made. Hence an understanding of the role of visual perception must of necessity involve consideration of the entire cycle.

It is assumed that activity of the eye-brain subsystem is anchored to the optic array, not to the so-called retinal image. When perceiving

is veridical, it is the result of a chain of specificities: nervous system activity is specific to optic array invariants and transformations which in turn are specific to the environment and the individual's relation to it. Further, it is assumed that when perceiving and control actions are highly skilled or automated, information specified by perceiving is mapped directly into action. Since control adjustments ultimately control optical variables, the system will be most efficient when the actions directly produce changes in the variables of stimulation that are most salient for self-motion perception.

The framework described above has not been dominant in guiding research in visual perception either historically or currently. A contrast with the generally accepted alternatives should be instructive.

The traditional approach to the study of perception began by identifying perception with phenomenal experience. It is assumed that perceptual experiences must be manifestations of nervous system activity, and that an understanding of the mechanisms mediating between the sensory organs and the higher centers of the brain would produce explanations of perceptual phenomena. In the case of vision, it is assumed that the distribution of light over the retina, i.e., the retinal image, is inadequate to account for perception. Modifiable mechanisms must process the retinally supplied data to arrive at a representation of the environment. Current versions of this approach are channel theory (to account for the nervous system mechanisms) and computational theory (to account for the processing). Thus, the emphasis is on only a part of the perception-action cycle: the eye-brain subsystem.

By contrast, perceiving is defined within the ecological approach in terms of a reciprocal relation between the individual and the surrounding environment. Perceiving is the more or less skillful activity of gaining information about the environment and one's relationships to it. An understanding of the role of visual perception in flight and flight simulation must, then, examine these relations over the entire pilot-environment system, rather than confining attention to what goes on in the nervous system. The event of perceiving does not go on in the brain; the brain participates in the event (Shaw, 1981) and must function within a set of constraints imposed by the structure of the environment, the individual, and the aircraft. As a result, an understanding of the information an individual must deal with is pro-paedeutic to an understanding of the role of the nervous system in the perception-action cycle, not vice versa.

What are the consequences for research of accepting the ecological approach? If the level of analysis of the pilot-environment relationship is critical to our understanding of sensitivity to and guidance of self motion, then we must choose a level that is reductionistic enough to allow controlled experimentation and yet not so reductionistic that we study phenomena more specific to laboratory conditions than to real-world situations.

Take as a starting point the following strong assertion: All actions are for the purpose of controlling perception. If perceiving guides locomotion, and locomotion makes available new information for perceiving, then we must deal with information pickup and production, not information processing. We must study not only the information

available to a pilot in visual stimulation, but also the information controlled by the pilot in performing a flight maneuver.

Over the past four years, we have embarked upon just such an approach. Basic to our paradigm is the assumption that the perception-action system cannot be understood without first discovering the information on which its efficient and accurate functioning depends. What follows is an account of how we have proceeded, what problems our particular approach has encountered, the success to date, and what is left undone.

Two separate but interrelated strategies have been explored in parallel, one inductive, the other deductive. The inductive strategy involves an ecological survey of control adjustments and optical variables produced by a pilot during a flight maneuver. Such data are available from flight recorders and from performance recordings during the operation of visual flight simulators. Analysis of these data can guide the design of both (1) psychophysical experiments in which optical variables are independent variables and observers make decisions about the kind of self motion displayed, and (2) interactive experiments in which pilots control the display and optical variables are recorded as dependent variables.

When a pilot makes a set of control adjustments, the aircraft will assume a certain path at a certain speed, and it is assumed that the pilot maintains the path and speed until he perceives that a change is desirable. Analysis of path segments can, then, determine what optical conditions a pilot produced and when he became dissatisfied with them. From this kind of retrospective analysis, one can infer what the pilot

intended to occur both optically and environmentally. In addition, his performance can be scored relative to instructions or task demands.

#### Problems and Possible Solutions

In addition to the common problems associated with transfer of data from one computer to another, two data reduction problems have been encountered: (1) finding path segments by using a computational procedure, and (2) dealing with the interaction of several optical variables changing simultaneously over time. Solutions to both problems are underway, but have progressed slowly because the survey analyses have always been given second priority to our judgment experiments. The computer programs developed to analyze simulator performance data and the optical metrics isolated in our reactive experiments will be directly applicable to our initial interactive studies.

Isolation of potentially useful optical variables is, of course, preliminary to testing for their perceptual effectiveness using either the inductive or deductive strategy. While it would have been possible to begin with the study of interactive control of optical variables, it has been our strategy to first discover what observers are sensitive to in reactive experiments. In addition to maintaining more precise control over visual stimulation, we have been able to narrow down the informational candidates to be used in future interactive studies by the simple assumption that a pilot cannot control what he cannot perceive. The deductive experiments have, therefore, been pursued within the framework of factorial contrasts among optical variables potentially useful in detecting a given kind of self motion.

Since self-motion perception is defined as the pickup of information about the relation between the moving self and the surrounding environment, the isolation of optical variables which lawfully specify the relation must necessarily involve quantification of the path speed and heading of the eye in concert with the structure of ground surface texture. This dual specification is exemplified in the separation of optical edge rate and flow rate as effective variables for perceived change in self speed (Warren, Owen, & Hettinger, 1982) and in the isolation of optical splay and texture density changes as effective for detecting change in altitude (Wolpert, Owen, & Warren, Experiment 3, this report).

In some cases, optical variables can be manipulated independently and the variables of interest remain invariant throughout an event. Such is the case with global optical flow rate and fractional loss in altitude when flow acceleration is cancelled (Hettinger, Owen, & Warren, Experiment 3, this report) and when levels of fractional change in flow rate and edge rate are crossed (Warren, Owen, & Hettinger, 1982).

A major difficulty in contrasting different optical variables as candidates for useful information, however, is the fact that they are often linked physically in ways that limit the number of degrees of freedom allowed in designing an experiment (see Warren & Owen, 1982). In many cases, when two variables are factorially crossed, a third variable of interest will appear in the diagonals of the two-factor matrix. Any interaction of the two primary independent variables is necessarily confounded with the secondary independent variable. In cases where one of the three variables has no effect on performance,

particular combinations of main effects and interactions can be interpreted unambiguously because the effects of the secondary variables become explanations of the interactions.

In other cases, making one variable invariant throughout an event will result in a second potentially useful variable increasing or decreasing during the event. When dealing with interrelated higher-order ratios, it is generally the case that maintaining control over one variable means losing control over several other candidates. Therefore, a particular significant result can be interpreted only with regard to other cases in which a confounded variable had no effect.

A second problem with factorial designs is the fact that variables which change throughout an event are indexed in the analysis by only a particular value, e.g., at the beginning of the event, at runway threshold, or at touchdown. When the event duration is under the observer's or the pilot's control, the value of the optical variable at a critical time can be radically different from the value noted in the design. Some variables can be held invariant during an event, but this alternative may not be satisfactory because it can change the very nature of the event under study. For example, holding fractional loss in altitude constant, rather than descent rate, results in mimicking helicopter approaches rather than fixed-wing approaches.

Since it is often ecologically valid for several variables to change during an event, and information pickup time will vary as a result of the rate of unfolding of an event, finding a way of dealing with the problem is preferable to avoiding it either by studying artificially constrained events or by sampling points arbitrarily during

ecologically valid events. Our current approach to the problem is to map performance into two-dimensional time series, so that the effects of the two optical variables of interest can be observed over time even though both are changing simultaneously. The effect of any within-event invariant can also be plotted in the two-space. This technique, though tedious, has already helped in identifying effects of secondary variables in the data from previous studies.

Lastly, prior to our work, there were no empirical precedents for choosing among the available metrics for higher-order variables. In our work on sensitivity to change in speed and altitude, we have considered three metrics: one arbitrary (feet, meters, knots), the other two optically available (eyeheight scaling and ground-texture scaling). We have developed, within the constraints described above, several strategies for determining whether a potentially available source of information affects performance in ways which suggest that it is functionally effective information (see Owen, Warren, Jensen, Mangold, & Hettinger, 1981; Owen, Warren, & Mangold, in press; Warren, Owen, & Hettinger, 1982; Wolpert, Owen, & Warren, Experiment 3, this report). Under different conditions of self motion and different task demands, both eyeheight and ground unit have proved to be effective metrics in accounting for the sensitivity of observers.

#### About Information-Specifying Mechanisms

Our approach does not, of course, deny that nervous system mechanisms are required for perception. Since perception is defined in terms of the reciprocal relation between individual and environment, any result of the study of self-motion perception will simultaneously address

questions about optical sources of information to which the person is sensitive and the nature of the perceptual system mechanisms which underlie that sensitivity. The function of the mechanisms is different than that ascribed by channel theory, computational theory, or any other mediational theory, however. Rather than operating on any kind of raw sensory data, it is assumed that nervous system activity is specific to higher-order information in stimulation, even when misperception occurs. It is further assumed that the mechanisms are "smart" perceptual mechanisms (Runeson, 1977), i.e., they serve specific purposes for the individual and they may take advantage of ecological linkages in stimulation.

From this perspective, a variety of issues related to information-specifying mechanisms can be addressed. Firstly, our results indicate that the mechanisms responsible for self-motion perception are sensitive to fractional rates of change in speed and altitude, rather than absolute rates of change. This mode of sensitivity has several advantages: (1) It is independent of any particular speed or altitude and rate of change in speed or altitude. (2) It is the same in every direction in the ambient optic array, regardless of the fact that local flow rates differ with the direction that an individual might be looking. The extent to which either of these possibilities is functionally the case demands further research. (3) In the case of approach to a surface, the inverse of fractional change in optical variables specifies time to collision. Since this information would be useful to a pilot in maintaining a margin of safety between himself and the ground or between himself and another plane, it deserves attention as a contributing factor in aviation mishaps (see Owen & Warren, in press).

Secondly, our data indicate that self-motion mechanisms operate on the basis of the law of diminishing returns, a phenomenon common to most perceptual sensitivities. In general, we find a functional version of Fechner's principle operating: equal ratio increases in the effective optical variable lead to equal interval improvements in performance, i.e., in accuracy and efficiency. It is, in fact, this logarithmic relationship which is allowing us to examine the performance structure in the interaction between two perceptually effective optical variables which are varying simultaneously, i.e., by plotting results in log-log coordinates over time.

Thirdly, we have found that self-speed perception is influenced by both flow rate and edge rate (Warren, Owen, & Hettlinger, 1982), even though the experience of change in self speed with increase or decrease in edge rate is illusory. Since optical discontinuities (edges, intersections) are necessary for the optical manifestation of a flow pattern, and since flow transformation is necessary to produce an edge rate, it is not surprising that sensitivities to the two optical variables are related. In evolutionary terms, this may be a result of the fact that flow rate and edge rate are typically linked for a terrestrial animal with a nearly constant eyeheight. This nearly perfect correlation could have allowed the evolution of a "smart" perceptual mechanism sensitive to edge rate in place of or, more likely, in addition to a flow-rate sensitive mechanism. Where there are redundant optical specifiers of self motion, there will be survival value in the development of sensitivity to the multiple sources of information.

The fact that we have found very large individual differences in flow-rate versus edge-rate sensitivity suggests that redundant systems may in fact be involved, and the relative sensitivity of the two mechanisms differs from person to person. Redundant sensitivity should generally be favorable, but edge-rate sensitivity can result in misperception of self-speed and perhaps altitude when the density of vegetation or cultural texture changes during low-level, nap-of-the earth, flight or during approach to a runway.

Fourthly, in spite of the fact that optical flow acceleration has been touted for nearly 30 years as a major source of information for detecting loss in altitude, our results indicate that it is not used (Experiment 2, this report), or worse, it interferes with descent detection (Experiment 3, this report). Since flow acceleration also specifies speed change, attention to it may be reserved for detecting variation in speed. Optical (perspectival) splay, on the other hand, specifies only change in one's own eyeheight. When only splay is available, performance is best; when splay is unavailable, performance is much poorer (Experiment 3). These operations converge on a mechanism sensitive to splay change as responsible for sensitivity to change in eyeheight.

Lastly, our approach has applications to the study of the mechanisms responsible for sensitivity to the optical flow pattern in two relatively unexplored areas. (1) An experiment reported by Denton (1973, 1974) suggests that adaptation to the higher flow rates encountered during low-level, high-speed flight will affect sensitivity to self motion. Adaptation provides a time-honored paradigm for the study of

perceptual mechanisms, and his findings deserve further attention in light of their implications for accidents due to collisions with the ground. (2) Several authors have proposed that mechanisms responsible for peripheral vision are specialized for self-motion sensitivity. Others have argued that central vision is just as good, if not more adequate. In view of implications for (a) night flying, when the central mechanisms are least sensitive, and (b) flight simulation where peripheral displays add expense or from which texture may be deleted to ensure concentration in the forward display, application of our tests for sensitivity to optical variables is also warranted. The approach we are exploring thus has the potential to contribute extensively to an understanding of both functional information and the mechanisms underlying attention to that information.

### The Research

Three experiments were completed in the period since the interim report (Owen, 1982). These are reported in detail in the final three sections of this report.

Experiment 1 is based on an earlier study (Owen et al., 1981) which indicated that fractional loss in flow rate was the effective information for detecting loss in speed. The present study was designed as a preliminary experiment to aid in selection of levels of optical and event-duration variables for several subsequent studies. In contrast with the Owen et al. (1981) experiment which held deceleration rate constant and allowed fractional loss in flow to accelerate, fractional loss was held constant by reducing the deceleration rate as speed decreased. This technique keeps the variable of major interest invariant within each event.

Two other optical variables were manipulated: initial global optical flow rate and global optical texture density. Flow rate was varied to determine whether sensitivity to fractional loss varies with the speed of the event. Optical density was varied with eyeheight constant to determine whether edge rate had any independent effect.

Levels of two event-duration variables were explored primarily for methodological reasons. Although real-world events typically undergo transformations from steady states, self-motion transformations in experiments typically are in progress when a test trial is initiated. If the observer's task is to distinguish steady-state events from those that undergo a specific kind of change, it might be supposed that the observer defaults to the "constant" report when the change is not detected. An error rate of approximately 20% in our earlier experiments suggested that some perceptual phenomenon connected with the abrupt onset of an event might be operating. For this reason, a 5-sec period of constant flow rate was introduced on half the trials, after which constant flow continued or deceleration occurred for the remainder of the event.

The other time variable was the duration of that part of the event during which the observer was instructed to distinguish constant speed from deceleration. Since information pickup time produced such well structured results in earlier studies, it was of interest to determine the effects of speed stress on performance.

The results of Experiment 1 indicated that all the independent variables except texture density have large effects on accuracy and reaction time. Of particular interest is the great improvement in

performance with the 5-sec constant-flow preview. If this effect occurs during breakout from low cloud cover or after looking up from instruments or controls, pilots would be well advised to observe the flow pattern for several seconds before initiating any corrective control adjustment. Exactly how long the recommended period should be will depend on further research.

Change of speed has not been of particular interest in aviation to date, but it is a dimension of evasiveness that will undoubtedly receive increased attention in the future. It has value for our purposes for four reasons: (1) Change in speed during level flight is optically simpler than other translational and rotational motions, and thus provides a good initiation to optically more complex situations. (2) It provides a region of contact with the literature on optical analysis of driving and driving simulation which is more extensive than the flight literature. (3) It provides a converging operation for tests with events in which eyeheight varies. Sensitivity to fractional rates of change when there is no time to collisions suggests that the former may provide a more appropriate account of sensitivity to loss in altitude than the latter. Perception of time to collision or critical rates of fractional change will still be important for initiating control actions to avoid ground contact or to flare before touchdown, however. (4) Maintaining a constant eyeheight at a constant speed is important during nap-of-the-earth flight, and adaptation to flow is a distinct possibility. Tests of loss in sensitivity to change in speed will provide an objective measure of the possibly detrimental effects and aftereffects of flow adaptation.

The second and third experiments were concerned with isolating optical information for loss in altitude and determining the functional metric (self scaled versus environment scaled) for specifying descent rate optically. The two studies are based on an earlier experiment in which descent rate was held constant (Owen, Warren, & Mangold, 1981; in press) and a preliminary experiment in which fractional loss in altitude was held constant (Hettinger, 1981; Hettinger, Owen, & Warren, 1982). The new experiments were conducted in parallel, and both compared the two kinds of descent events explored in the earlier studies.

The purpose of Experiment 2 was to assess the usefulness of global optical flow acceleration by contrasting conditions in which it is present versus absent. Holding optical flow constant also holds fractional loss in altitude constant within an event. As a result, the remaining optical specifiers of descent, rate of increase in global perspectival splay angle and fractional rate of decrease in global optical texture density, become within-event invariants as well.

Three levels of initial optical flow rate and two levels of initial optical texture density were chosen to mimic conditions appropriate to flight at different altitudes over ground texture elements of different sizes. Since surreptitiously recorded reaction times had shown the same structure as detection accuracy in the earlier studies, event durations of 2, 4, and 8 sec were used to assess the effects of speed stress on sensitivity.

The goals of Experiment 3 were twofold: (1) to test the perceptual effectiveness of the three optical variables which vary with change in altitude, and (2) to contrast eyeheight-scaled with ground-texture-

scaled specification of descent rate as perceptually effective metrics for optical self-motion information. Optical flow acceleration was eliminated on half the trials by slowing down on a linear path slope. Optical splay was eliminated by using only texture parallel to the horizon, so that there were no optical discontinuities to specify perspective transformations during descent. In conditions where optical acceleration and splay were both eliminated, only change in optical density of the horizontal strips remained. Lastly, increase in optical splay was the only information for descent when horizontal texture and flow acceleration were eliminated.

The set of operations used to contrast the three types of information which had previously been mathematically isolated show how the combination of self-motion variables and environmental surface-texture variables can be used to break optical linkages for experimental purposes. Cast in terms of a different descriptive system, we have separated three aspects of optical magnification or expansion (Gibson, 1955, 1958). Optical magnification typically occurs in every direction, i.e., radially, about the focus of expansion. Optical flow rate specifies the rate of optical expansion. By using rectilinear texture with edges parallel to either the horizon or the direction of travel, we have decomposed the pattern of magnification into two components: (1) increase in size in the optical texture gradient representing horizontal-only strips, and (2) increase in size of the optical splay angle between the perspectival representations of vertical-only strips. Constraints on surface texture and the simulated path of the eye in turn constrain the flow pattern so that only some aspects of typical magnification are manifested.

In this fashion, the optical flow pattern can be decomposed to test whether novices can be taught to attend to information specifying descent. If so, the technique could be used in simulator training, with transfer to events containing information irrelevant to descent detection, e.g., edge rate and the forward speed component of flow rate.

In Experiment 2 altitude loss was initiated immediately, as in previous studies, whereas in Experiment 3, descent followed a 5-sec preview of level flight at a constant speed. Since the fractional losses and flow rates were comparable in the two experiments, it was legitimate to contrast the results as reflecting the effect of preview versus no preview. The effect was the same as in Experiment 1, except much greater: Error rates averaged 19% lower with the 5-sec preview. Again, in view of its implications for breaking out of cloud cover and looking outside after dealing with instruments or controls, this finding demands further investigation.

### Conclusion

The successful application of the research paradigm developed as part of this project and exemplified by the three experiments described herein, as well as those presented in the two previous reports (Owen, Jensen, 1981; Owen, 1982), is only a beginning. More interesting problems arise in generalization of the approach to the problems of three-dimensional ground surfaces and objects involved in nap-of-the-earth flight with hill or ridge crossings and avoidance of trees, rocks, and man-made structures. The tests of sensitivity to change in self motion that we have developed will also serve to assess the effects of prior experience. Examples are the potentially negative effects of adaptation, with implications

for aviation safety, and the potentially positive effects of perceptual learning, with implications for flight training.

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EXPERIMENT 1

Methodological Considerations of Constant Fractional Loss in Flow Rate  
and Event Duration Variables in Detecting Decelerating Self Motion

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Introduction

Background

James J. Gibson has explored the phenomenon of self-motion perception in accordance with his ecological approach to visual perception. He outlined a general theory of the visual perception and control of locomotion (Gibson, 1958) based upon the assertion that the visual systems of all animals have evolved to be sensitive to light reflected from surfaces in the environment. This ambient light is given structure and pattern by virtue of the qualities of the objects from which it reflects. Rays of reflected light converge at every point in the medium. Therefore, the objective information about the environment is available to an eye occupying any place of observation in the environment. Gibson (1958, 1961) termed the pattern of differential reflectances projected to the eye an optic array. The animal equipped with an ocular system may actively explore the optic array to glean information carried by variables in it (Gibson, 1961).

The observation place of the eye of a moving animal is always changing, therefore a continuous family of transformations is available to this mobile eye. Gibson calls the projection of the environment to movement along a path of

observation the flow pattern of the optic array. Information for self motion is inherent in the pattern and changes of pattern in the globally changing optic array, or optical flow field. For example, a centrifugal flow of the optical flow field from a pole in the direction of displacement is characteristic of forward self motion (Gibson, 1963). The global optical flow field transformation is labeled motion perspective (Gibson, 1968; Gibson, Olum & Rosenblatt, 1955). Motion perspective elicits a perception of self rather than object movement because transformation occurs in the whole of the optic array. Object movement is specified by change only in a specific section of the ambient optic array.

Motion perspective can be analyzed for an ambient optic array along a path of observation which is unoccupied, i.e., it is an abstract way of describing the motion information inherent in a theoretical optical flow field. Alternatively, visual kinesthesia carries information for perceiving the layout of the environment in tandem with perceiving the self (Gibson, 1979). Information for visual kinesthesia is available for a passive observer as well as an active observer. For example, a passenger in the cockpit of an airplane experiences visual kinesthesia in the same manner as does the pilot, who is in active control of self motion.

Variables in the global optical flow pattern are also specific to the properties of the environment. Gibson states that lower-order variables (such as wavelengths) combine in the light to yield higher-order variables (such as ratios or proportions) to which the visual system is sensitive (Gibson, 1966). Higher-order variables provide information about relative orientations, sizes, and distances of environmental surfaces and objects. As an animal continually moves about in the environment, some but not all of the properties of the flow pattern change. Those properties which undergo change are termed varying variables, while invariant

variables are those which do not change as the observer moves (Gibson, 1961). Variants and invariants in an optic array hold potential information for a visual system. The active observer explores the environment to obtain the information inherent in both of these types of variables. The visual system is able to separate permanence from change in the optic array. By this isolation of invariants, information about the environment is obtained. Order is inherent in the light in the form of higher-order variables to which the perceiver is sensitive. The patterns of invariant and varying variables are produced by active exploration, and contain information about the environment which exists in the structured light of the optic array (Gibson, 1963).

A visual system sensitive to invariants provides the organism with three basic types of information. Exterospecific information indicates the environmental layout and events external to the observer. Propriospecific information tells of the observer's own actions (Gibson, 1966). To these two classifications of information, Lee (1980) added expropriospecific information, which is indicative of the orientation and/or movement of the body of the observer relative to the environment.

#### Empirical self-motion research

Empirical investigations of the perception of self motion have been undertaken in a variety of settings. Denton (1976), Salvatore (1968), and Evans (1970, a & b) each dealt with estimation of automobile velocity, but none of these experiments examined optical specifiers of self motion. Lee (1976, 1980) has developed a mathematical analysis of the global optical flow field, in an attempt to determine the relationship between optical variables of this flow field and variables specific to the layout of the environment. Following Gibson's lead, Lee

asserted that animals make use of body-scaled information from the optical flow field. Sizes and distances of environmental surfaces and objects are specified in units of the animal's eye height by a specific relation between the optical flow from texture elements in the optic array (Lee, 1980). In particular, he discusses the visual information necessary for the control of braking. The higher-order optical variable  $\tau(t)$  (which is the rate of angular size change over time) specifies information about the time-to-contact with a surface in the environment. Sensitivity to this higher-order information in the light may be what allows visual control of steering, braking and self motion which may or may not be mediated by a vehicle (Lee, 1976).

In a study of simulated looming of an object, Schiff & Detwiler (1979) reach a conclusion similar to that of Lee, i.e. observers make use of two-dimensional spatiotemporal information about the rate of angular size change to predict time-to-collision. Distance-related three-dimensional information was found not to be related to judgements. Their findings show a constant underestimation of time-to-collision, and they propose that a proportional error constant might be added to Lee's mathematical formulations to account for the apparent nonuse of information beyond approximately 10 seconds from contact time. Two-dimensional information yielded invariant results over several object velocities, sizes, and distances, thereby demonstrating that the higher-order rather than lower-order information is the functional optical invariant to which observers are sensitive. Because of the absence of the centrifugal flow of textural information which specifies self motion, Schiff & Detwiler note that these results may only apply to stationary observers and looming objects.

Although experimental investigations manipulating global optical texture density as a between-event independent variable were not found in the literature, Denton (1980) manipulated certain optical specifiers of self motion within events in experiments conducted with the use of a driving simulator. He varied the spacing of stripes on the simulated roadway within events in an attempt to counteract the effects of adaptation to speed of self motion. His results cannot be taken as conclusive, however, because he failed to include a control condition with evenly-spaced stripes. This investigation obtains its significance in that optical information for self-motion perception was manipulated in attempts to affect performance. Denton indicated that the visual system must be sensitive to relative rates of movement (Denton, 1980).

#### Introduction to the present study

Optical information for relative change in speed during self motion may be specified by one or more of several candidates proposed by Warren (1982). He hypothesized that global optical flow rate (pathspeed scaled in eye heights per second) primarily corresponds to perceived self motion. Owen, Warren, Jensen, Mangold, & Hettinger (1981) used his systematization as a guide in order to search for the most effective optical information for detecting loss in speed during level self motion. They used three values each of three environmental variables (speed,  $x$ ; deceleration,  $\dot{x}$ ; and altitude,  $z$ ) as primary independent variables to construct matrices with five levels of each of the three optical flow variables (initial global optical flow rate,  $\dot{x}_0/z$ ; global optical flow deceleration,  $\ddot{x}_t/z$ , and initial fractional loss in flow rate,  $\ddot{x}_t/\dot{x}_0$ ), which are secondary independent variables. Assessment of the optical variables is possible through this design, as is investigation of the status of each one as a functional optical invariant. A functional optical invariant

was operationally defined as one for which consistent performance is obtained, although the environmental variables contributing to the ratios vary over a wide range. Fractional loss in flow was found to meet the criteria for a functional optical invariant. Owen, et al. label their finding as being consistent with other experiments done in the ecological framework: the relevant information is not merely rate of change of flow, but is rather relative rate of change in flow.

The experiment completed by Owen, et al. stirred curiosities regarding this discovery of the importance of optical information specified by fractional loss in flow rate. When deceleration was simulated in their experiment, it was done so in only one manner: the environmental variable of deceleration ( $\dot{x}_t$ ) was held constant. When this is the case, the displayed event represents deceleration, but fractional loss in flow rate ( $\dot{x}_t/\dot{x}_0$ ) will necessarily increase throughout the duration of the event. The value of fractional loss at reaction time, then, is under the control of the observer. The systematic increase of fractional loss in flow could affect performance by making the detection of deceleration progressively easier the longer the event is displayed. This fact necessitates an investigation into whether performance would be significantly affected if deceleration were shown in an alternate way: by holding fractional loss in flow constant throughout the duration of the event. When this is the case, its value at reaction time is under the control of the experimenter. Here deceleration must decrease as speed decreases in order to hold their ratio invariant. The present study contrasts both these methods of displaying optical deceleration in an attempt to assess the results and conclusions of the Owen et al. study. Figure 1 shows how fractional loss in flow increases throughout four events when deceleration is held constant

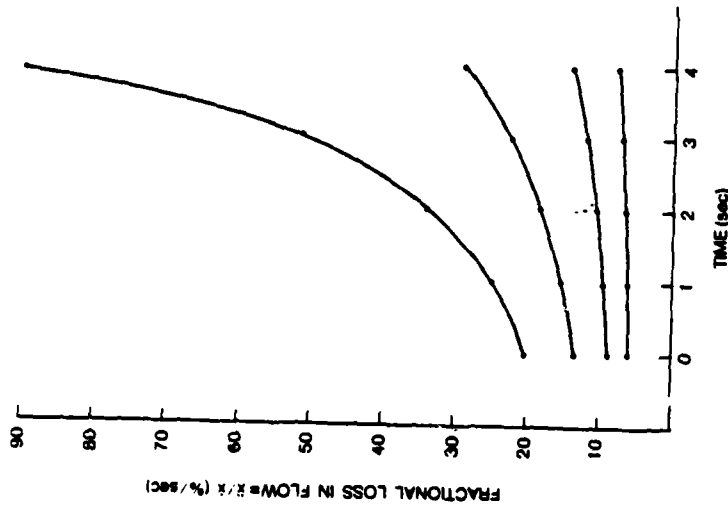


Figure 1. Fractional losses for four events (initial fractional losses of 20.25, 13.5, 9, and 6%/sec) when deceleration is constant.

$\dot{x}_r = K$	$\ddot{x}_r = K$	$(\ddot{x}_r/\dot{x}_r) = K$
Exp. 1	Exp. 1	Exp. 1
Exp. 2	Exp. 2	Exp. 2
Exp. 2	Exp. 2	Exp. 2

$(\ddot{x}_0/\dot{x}_0)$   $(\ddot{x}_0/z)$   $(z/g)$

$(\ddot{x}_0/\dot{x}_0)$   $(\ddot{x}_0/z)$   $(z/g)$

Figure 2. Experimental design.

( $x = k$ ). (Setting a variable equal to  $k$  indicates that the value of the variable is invariant over time.)

Rather than crossing environmental variables as primary independent variables and allowing optical variables to result as secondary independent variables (See Warren & Owen, 1982), this study introduces a new method of research on decelerating self motion. This method has proved fruitful in the investigation of detection of descending self motion (Hettinger, 1981). The primary independent variables are optical variables, so the resulting secondary independent variables are those environmental variables comprising them, along with the remaining optical variables which necessarily exist given the values of the primary independent optical variables. This technique lends better factorial control over the information to which observers are potentially sensitive, regardless of what environmental variables must join to create them.

Utilizing this method of factorially crossing optical variables, the present study will also attempt to assess whether sensitivity to fractional loss in flow is independent of global optical texture density ( $z/g$ ), global optical flow deceleration ( $\dot{x}_0/z$ ), and global optical flow rate ( $\dot{x}_0/z$ ). Since the latter two cannot be orthogonally crossed (see Warren & Owen, 1982), their assessment cannot be made through a simple factorial crossing. Circumvention of this constraint necessitates two  $3^3$  factorial designs. One crosses three levels of fractional loss in flow, three levels of initial global optical flow rate, and three levels of global optical texture density. The second is identical, except three values of initial global optical flow deceleration are substituted for those of global optical flow rate. To contrast the two different methods of displaying decelerating self motion, the decelerating events in each crossing were displayed

in two ways: with a constant deceleration, and with a constant fractional loss in flow rate. When deceleration is held constant, it and edge rate deceleration ( $\ddot{x}_f/g$ ) are both within-event invariants. When fractional loss in flow ( $\ddot{x}/z/\dot{x}/z$ ) is held constant over texture that is regularly spaced in the  $x$  dimension, fractional loss in speed and fractional loss in edge rate ( $\ddot{x}/g/\dot{x}/g$ ) are necessarily held constant also, so that the three rates of change will be identical. An illustration of the designs for both Experiments 1 and 2 are shown in Figure 2.

The events in the study by Owen et al. (1981) all commenced directly from a blank screen. Research by Runeson (1974, 1975) indicated that there are discrepancies between physical and perceived velocities. Although his research was primarily concerned with object-motion perception rather than the perception of self motion, his findings may be relevant to self-motion research. He has found that a movement with constant velocity appears to accelerate at its onset and to later slow to a constant speed. Runeson (1975) concluded that "the perceptual concept of velocity seems to differ from the physical concept through the inclusion or presupposition of a natural start" (p. 261). A natural motion is one which starts with a smooth acceleration and then reaches and maintains a constant velocity. He observed that such a complicated motion function is common to a natural terrestrial environment. Since constant velocity has been found not to be perceived as such, possibilities are raised as to the reason for the error rate of approximately 20% for judgments of constant-speed events found by Owen et al. (1981). Events with a constant speed may appear to decelerate if the observer's perceptual system is sensitive primarily to motions with a natural start.

A method which should illuminate this issue is one in which the event begins with a period of constant motion, and subsequently either changes to deceleration or remains constant. Sensitivity to change in speed may be different under this condition than it would be under the condition of no initial period of constant speed. The contrast of change with no change may be detected differently than would the contrast of change with ongoing change. Both conditions are ecologically valid: the first mimics breaking out of a cloud while flying, whereas the second represents loss in speed after traveling for a period of time at a constant speed (e.g., due to the application of a speed brake). If sensitivity to these two conditions differs significantly, both the design of new experiments and the interpretation of earlier results will be affected.

## Method

### Apparatus and Events

A special purpose computer generated real-time transformations in a video projection display of 5 to 15-sec events representing level self motion at an altitude of 70 m over a flat ground surface consisting of a rectilinear island 30.72 km long. The island was covered with square texture blocks of light green, dark green, light brown, and dark brown. The number of edges in the direction of travel was fixed at 20, so the width of the island was a function of the three texture block sizes: 15.56 m, 23.33 m, and 35 m. The corresponding island widths were 295.64 m, 443.27 m, 665 m, respectively. The colors were randomly assigned to the texture blocks with the constraint that no two texture blocks of the same color would be adjacent. The simulated sky was blue-gray, while the non-textured area surrounding the island was dark gray. The field of view available from the stationary Singer-Link GAT-1 simulator was 34.3 deg wide by 26.1 deg high when viewed from a distance of 2.43 m. The horizon was 1.96 m from the floor at the screen's center, approximating the observer's eye level.

### Design

Experiment 1 is a preliminary experiment which was conducted to choose levels of optical variables which would be suitable for the second experiment. The design of Experiment 1 is contained in the cells on the upper left and upper right of Figure 2, i.e., it utilizes the factorial crossing of fractional loss in flow rate, initial global optical flow rate, and global optical texture density. Deceleration is displayed in only one way: fractional loss in flow rate is held constant throughout each event according to the following formula:

$$\dot{x}_t = \dot{x}_0 / [1 - (\dot{x}_0/\dot{x}_0)t] \quad (1)$$

See Tables 1, 2, and 3 for examples of time series using hypothetical values associated with constant flow, constant flow deceleration and constant fractional loss in flow rate, respectively.

In order to allow the choice of the levels for fractional loss in flow rate from a wide range, four values were taken from within the range utilized in the Owen et al. study  $(\dot{x}/\dot{x})_t = 6.00, 9.00, 13.50, \text{ and } 20.25\%/ \text{sec}$ . They were then fully crossed with three levels of initial global optical flow rate  $(\dot{x}_0/z = .4, .6, \text{ and } .9 \text{ h/sec})$ , and three levels of global optical texture density  $(z/g = 2, 3, \text{ and } 4.5 \text{ g/h})$ . These last three values were always within-event invariants, because the simulated self motion maintained a constant altitude ( $z = 70 \text{ m}$ ). These  $4 \times 3 \times 3$  crossings alone yielded 36 decelerating events.

In previous experiments event durations were constrained by how long the event parameters allowed the event to last before stopping. In order to investigate the impact on error rates and reaction times of events with various durations, three core durations (core duration = 5, 7.5, and 10 sec) were included in the design. In anticipation of the second experiment where deceleration is held constant, some of the fractional losses in flow rate were not shown for some of the longer core durations. For example, when deceleration is held constant, an event with a fractional loss in flow of 13.5%/sec halts in 7.5 sec. Therefore, the four levels of fractional loss in flow were only partially crossed with core duration. That is, fractional losses in flow of 6.00, 13.50, and 20.25%/sec were displayed only for core durations of 10, 7.5, and 5 sec, respectively. In order to provide a balanced contrast, events with fractional loss in flow of 9.00%/sec and those with a constant flow (fractional loss in flow = 0%/sec) were displayed at all

Table 1

Values of Environmental and Optical Variables at Time T for Two  
Events with Constant Optical Flow at an Altitude of 70 m

THIS IS A TIME SERIES FOR APL-8, SHOWING VARIABLE VALUES AT A CONSTANT  
ALTITUDE (Z) OF 70 METERS.

(VELOCITY REMAINS CONSTANT THROUGHOUT EACH INDIVIDUAL EVENT)

GROUND TEXTURE SIZE IS CONSTANT AT 23.333 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/H/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
1	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
2	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
3	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
4	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
5	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
6	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
7	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
8	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
9	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00
10	42.000	0.000	0.00	0.60	0.0000	1.8000	0.0000	3.00

GROUND TEXTURE SIZE IS CONSTANT AT 35 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/H/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
1	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
2	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
3	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
4	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
5	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
6	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
7	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
8	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
9	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00
10	63.000	0.000	0.00	0.90	0.0000	1.8000	0.0000	2.00

Table 2

Values of Environmental and Optical Variables at Time T for Two Events with Constant Flow Deceleration at an Altitude of 70 m

THIS IS A TIME SERIES FOR APL-8, SHOWING VARIABLE VALUES AT A CONSTANT ALTITUDE (Z) OF 70 METERS.

(DECELERATION REMAINS CONSTANT THROUGHOUT EACH INDIVIDUAL EVENT)

GROUND TEXTURE SIZE IS CONSTANT AT 23.333 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	42.000	-3.780	-9.00	0.60	-0.0540	1.8000	-0.1620	3.00
1	38.220	-3.780	-9.89	0.55	-0.0540	1.6380	-0.1620	3.00
2	34.440	-3.780	-10.98	0.49	-0.0540	1.4760	-0.1620	3.00
3	30.660	-3.780	-12.33	0.44	-0.0540	1.3140	-0.1620	3.00
4	26.880	-3.780	-14.06	0.38	-0.0540	1.1520	-0.1620	3.00
5	23.100	-3.780	-16.36	0.33	-0.0540	0.9900	-0.1620	3.00
6	19.320	-3.780	-19.57	0.28	-0.0540	0.8280	-0.1620	3.00
7	15.540	-3.780	-24.32	0.22	-0.0540	0.6660	-0.1620	3.00
8	11.760	-3.780	-32.14	0.17	-0.0540	0.5040	-0.1620	3.00
9	7.980	-3.780	-47.37	0.11	-0.0540	0.3420	-0.1620	3.00
10	4.200	-3.780	-90.00	0.06	-0.0540	0.1800	-0.1620	3.00

GROUND TEXTURE SIZE IS CONSTANT AT 35 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	63.000	-8.505	-13.50	0.90	-0.1215	1.8000	-0.2430	2.00
1	54.495	-8.505	-15.61	0.78	-0.1215	1.5570	-0.2430	2.00
2	45.990	-8.505	-18.49	0.66	-0.1215	1.3140	-0.2430	2.00
3	37.485	-8.505	-22.69	0.54	-0.1215	1.0710	-0.2430	2.00
4	28.980	-8.505	-29.35	0.41	-0.1215	0.8280	-0.2430	2.00
5	20.475	-8.505	-41.54	0.29	-0.1215	0.5850	-0.2430	2.00
6	11.970	-8.505	-71.05	0.17	-0.1215	0.3420	-0.2430	2.00
7	3.465	-8.505	-245.45	0.05	-0.1215	0.0990	-0.2430	2.00

SCENE STOPS HERE

Table 3

Values of Environmental and Optical Variables at Time T for Two Events with Constant Fractional Loss in Flow at an Altitude of 70 m

THIS IS A TIME SERIES FOR APL-3, SHOWING VARIABLE VALUES AT A CONSTANT ALTITUDE (Z) OF 70 METERS.

(FRACTIONAL LOSS IN SPEED REMAINS CONSTANT THROUGHOUT EACH INDIVIDUAL EVENT

GROUND TEXTURE SIZE IS CONSTANT AT 23.333 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	42.000	-3.780	-9.00	0.60	-0.0540	1.8000	-0.1620	3.00
1	38.532	-3.468	-9.00	0.55	-0.0495	1.6514	-0.1486	3.00
2	35.593	-3.203	-9.00	0.51	-0.0458	1.5254	-0.1373	3.00
3	33.071	-2.976	-9.00	0.47	-0.0425	1.4173	-0.1276	3.00
4	30.882	-2.779	-9.00	0.44	-0.0397	1.3235	-0.1191	3.00
5	28.966	-2.607	-9.00	0.41	-0.0372	1.2414	-0.1117	3.00
6	27.273	-2.455	-9.00	0.39	-0.0351	1.1698	-0.1052	3.00
7	25.767	-2.319	-9.00	0.37	-0.0331	1.1043	-0.0994	3.00
8	24.419	-2.198	-9.00	0.35	-0.0314	1.0465	-0.0942	3.00
9	23.204	-2.088	-9.00	0.33	-0.0298	0.9945	-0.0895	3.00
10	22.105	-1.989	-9.00	0.32	-0.0284	0.9474	-0.0853	3.00

GROUND TEXTURE SIZE IS CONSTANT AT 35 METERS DURING THIS EVENT.

T (SEC)	X' (M/SEC)	X'' (M/SEC <sup>2</sup> )	X'''/X' (%/SEC)	X''/Z (H/SEC)	X'''/Z (H/SEC <sup>2</sup> )	X'/G (G/SEC)	X''/G (G/SEC <sup>2</sup> )	Z/G (G/H)
0	63.000	-8.505	-13.50	0.90	-0.1215	1.8000	-0.2430	2.00
1	55.507	-7.493	-13.50	0.79	-0.1070	1.5859	-0.2141	2.00
2	49.606	-6.697	-13.50	0.71	-0.0957	1.4173	-0.1913	2.00
3	44.840	-6.053	-13.50	0.64	-0.0865	1.2811	-0.1730	2.00
4	40.909	-5.523	-13.50	0.58	-0.0789	1.1688	-0.1578	2.00
5	37.612	-5.078	-13.50	0.54	-0.0725	1.0746	-0.1451	2.00
6	34.807	-4.699	-13.50	0.50	-0.0671	0.9945	-0.1343	2.00
7	32.391	-4.373	-13.50	0.46	-0.0625	0.9254	-0.1249	2.00
8	30.288	-4.089	-13.50	0.43	-0.0584	0.8654	-0.1168	2.00
9	28.442	-3.840	-13.50	0.41	-0.0549	0.8126	-0.1097	2.00
10	26.809	-3.619	-13.50	0.38	-0.0517	0.7660	-0.1034	2.00



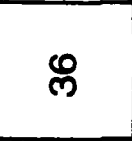

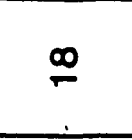
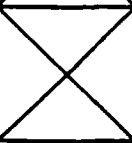
three core durations. Table 4 illustrates the crossing of core duration and fractional loss in flow for Experiment 1. (Constant events were included as many times as was necessary to match the number of initial speeds of the decelerating events.)

The design also included the variable initial duration, discussed earlier. Each event was displayed once with an initial duration of 0 sec and once with an initial duration of 5 sec. Events were blocked by initial duration, and the events within each were randomized twice with the constraint that no more than four constant-speed or four decelerating events could occur in sequence, resulting in four random orders. Eight combinations of the four randomizations were repeated four times, for a total of 32 observers. A complete inventory of displayed events and mean performance is shown in Appendix A. Nine practice events with optical parameters similar to those of the experimental events were displayed prior to each block of actual testing, for a total of 18 practice events per observer.

#### Procedure

Half of the observers viewed a block of events with initial durations of 5 sec, followed by a block of events with initial durations of 0 sec, while the other half received the reverse order. A set of instructions appropriate only to the block of events which would immediately follow was read aloud by the experimenter. The instructions preceding the block of events with initial durations of 5 sec indicated that the observer should make a judgment about each event only after a tone indicating the end of the 5-sec period of constant-speed travel. In contrast, the instructions preceding the block of events with 0-sec initial durations advised the observers to respond as soon as they had made a decision. (See Appendix B for the complete instructions.)

Table 4. Crossing of fractional loss in flow and core duration. Numbers in cells indicate number of events presented to each observer, including both initial durations. Cells crossed out were not included in the design.

FRACTIONAL LOSS IN FLOW = $\dot{x}/\bar{x}$ (%/sec)						
		0	6.00	9.00	13.50	20.25
CORE DURATION (sec)	5.0	36		18		18
	7.5	36		18	18	
	10.0	36	18	18		

An individual trial consisted of a verbal ready signal, followed by the presentation of an event. The observer was instructed to indicate a judgment of whether the event represented decelerating or constant-speed travel by pressing one of two buttons on a hand-held response box. In addition to recording the observer's decision, the button press stopped a millisecond timer which was started at the beginning of the core duration period (i.e., immediately in the 0-sec initial duration block, and after 5 sec in the 5-sec initial duration block), thereby surreptitiously recording the response time for each event. Following each judgment, the observer was to indicate aloud to the experimenter a confidence rating of "1," "2," or "3," indicating whether he or she was guessing at, fairly certain of, or very certain of the judgment. No feedback was provided during the entire experiment.

#### Observers

Observers were 32 undergraduate students (16 males, 16 females) at the Ohio State University who participated in the experiment in partial fulfillment of an introductory psychology course requirement. Each claimed no previous simulator or piloting experience.

### Results

The following summary scores were computed for each cell in the experimental design: proportion error, mean reaction time for all events (correct plus error), and mean reaction time for error - free events only. Proportion error scores and error-free reaction times came from completely different events, and together they comprised the entire set of events. These two dependent variables were selected for detailed presentation on this basis. Mean reaction times subsequently discussed are correct reaction times unless otherwise noted.

Due to the large number of judgments made in experiments of this type, many of the independent variable effects may reach traditional levels of statistical significance and yet account for only a negligible part of the total variance. Therefore, independent variables which accounted for at least 1.5% of the total variance in the design are the only effects discussed. All these effects achieved at least the  $p < .001$  level of significance. (Refer to Appendix C for analysis of variance summary tables containing individual values.)

Five repeated-measures analyses of variance were performed for each of the two dependent variables: one for decelerating events in each of the three core durations, one for constant-flow events only, and one for constant-flow events versus events with a fractional loss in flow rate of 9%/sec. The last analysis served the purpose of comparing events over core durations, in that these were the only values of fractional loss which were displayed for all three core durations (see Table 4). Sex of the observers was treated as a grouping factor in each analysis, but nowhere in the analyses did sex result in a significant difference in performance.

As Figures 3 and 4 show, when the core duration was 5 sec, error rate was reduced by approximately 24% and reaction time was reduced by at least .5 sec with increases in fractional loss in flow rate (which remained constant within an event), accounting for 6.5% and 2.3% of the respective variances. When the core duration was 10 sec, an increase in fractional loss from 9 to 13.5%/sec produced a 19% decrease in error rate, accounting for 3.7% of the variance.

Figure 4 also illustrates that an initial duration of 5 sec resulted in a decrease in mean reaction time for each core duration, accounting for 18.4, 12.6, and 15.7% of the variance in the analyses for core durations of 5, 7.5, and 10 sec, respectively. On the average, error rate decreased by approximately 16 and 12% with addition of an initial duration of 5 sec in the analyses for core durations of 5 and 7.5 sec, respectively (see Figure 3). The main effect of initial duration accounted for 3.0% and 1.7% of the variance in the respective analyses.

Figure 5 illustrates differences in error rates for constant-flow events due to differences in global optical flow rates between events. Faster flow rates tended to result in more accurate detection of constant speed. Error rates dropped an average of 9.25% from a flow rate of .4 to one of .6, and decreased an average of 6.5% from a flow rate of .6 to one of .9. This effect accounted for 2.1% of the total variance, and is the only place in all the analyses where global optical flow rate affected performance significantly.

Figure 6 shows an 18% drop in error rate for events with a constant flow relative to events with a fractional loss in flow of 9%/sec. The main effect of fractional loss in flow rate accounted for 4.7% of the total variance. In the constant-flow condition, a higher proportion of (correct) "constant" reports was made after a 5 sec initial duration, while a lower proportion of (incorrect)

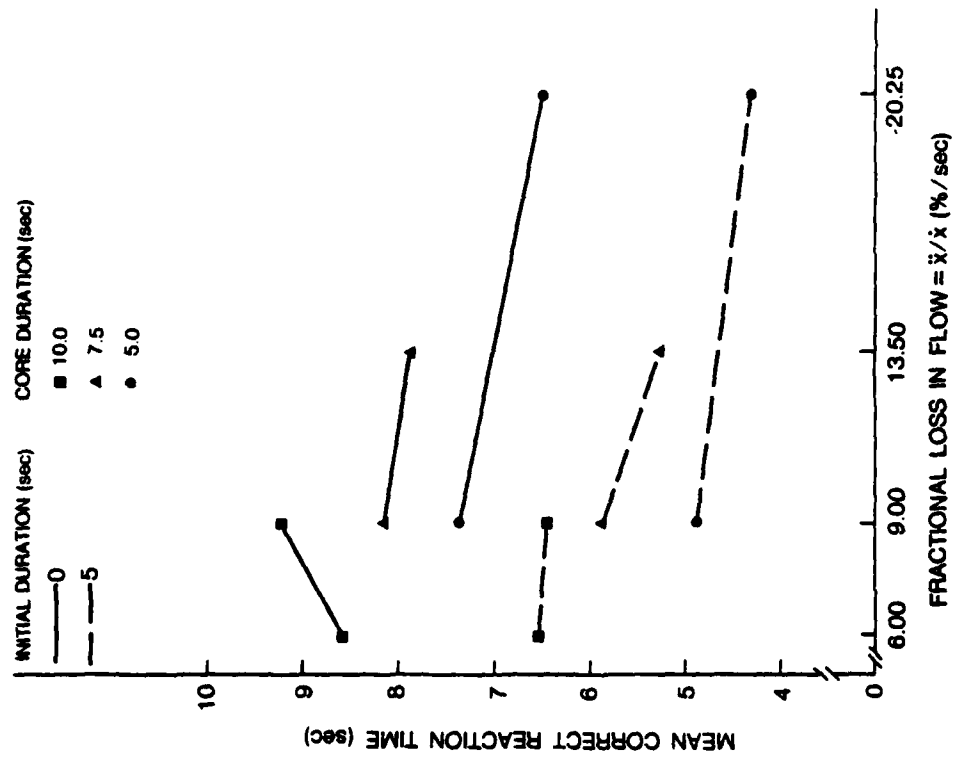


Figure 4. Mean correct reaction times for decelerating events only, for crossings of initial duration, core duration, and fractional loss in flow rate.

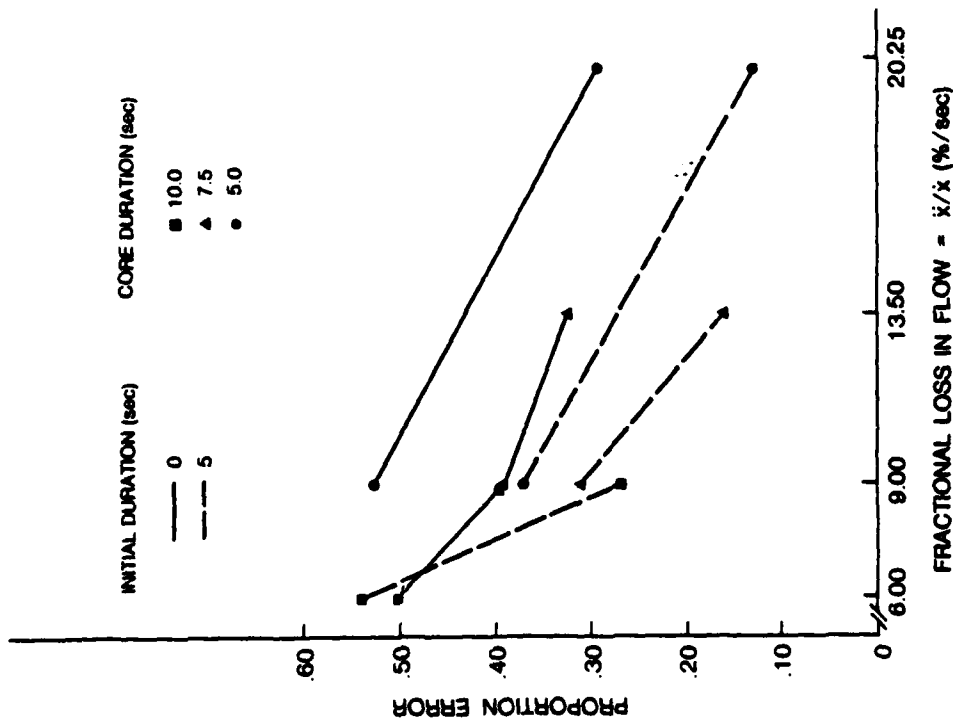


Figure 3. Proportion error for decelerating events only, for crossings of initial duration, core duration, and fractional loss in flow rate.

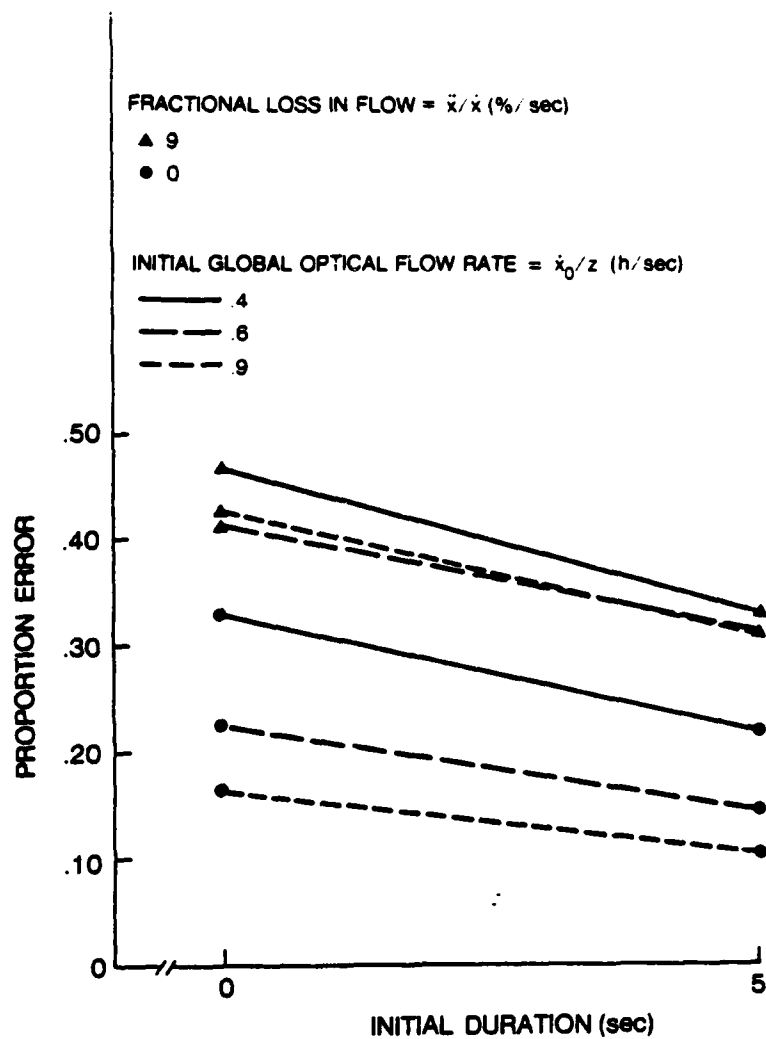


Figure 5. Proportion error for 0 and 9%/sec fractional losses crossed with initial global optical flow rate and initial duration.

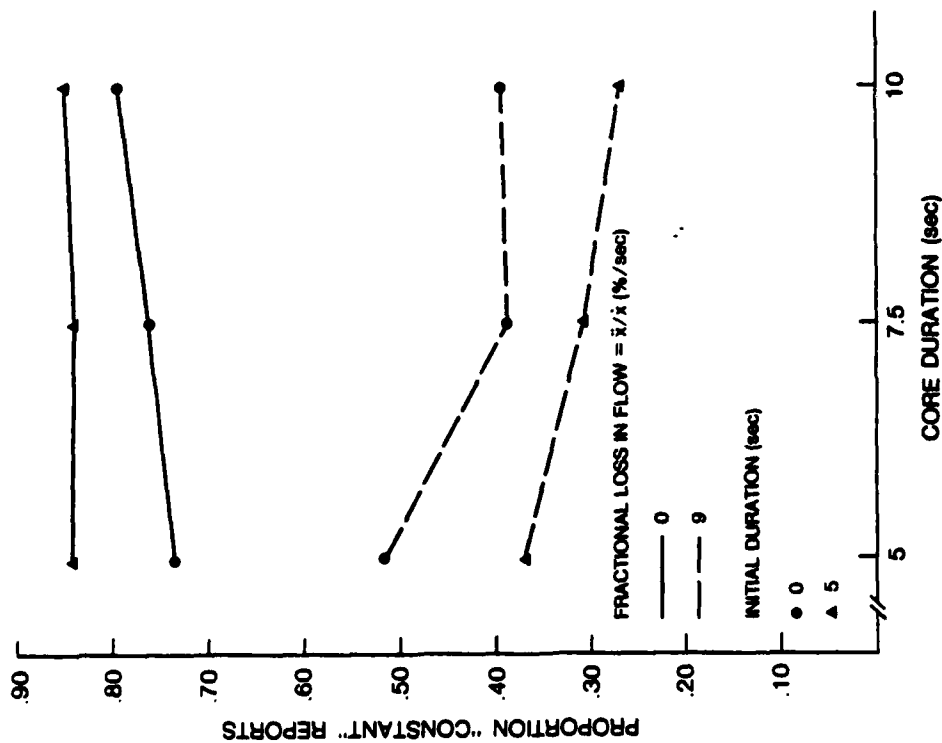


Figure 6. Proportion "constant" reports for 0 and 9%/sec fractional losses crossed with initial duration and core duration.

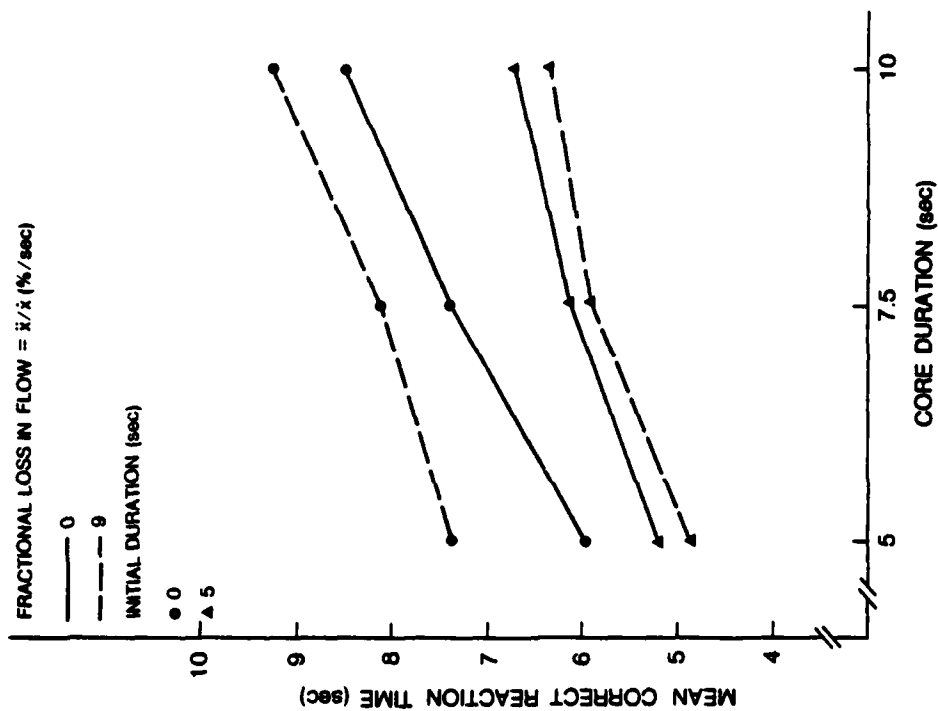


Figure 7. Mean correct reaction times for 0 and 9%/sec fractional losses crossed with initial duration and core duration.

"constant" reports was made to events with a 9%/sec fractional loss in flow after the 5 sec initial duration. With the preview, performance improved 7.8% in the constant-flow condition, and 11.4% for the 9%/sec fractional loss condition. The main effect of an initial duration accounted for 1.5% of the total variance.

The effect of initial duration on reaction times for the same analysis is illustrated in Figure 7. An initial duration of 5 sec resulted in an average drop in reaction times to constant-flow events of 1.25 sec. Reaction times to events with a fractional loss of 9%/sec were faster on the average by 2.75 sec. The main effect of initial duration accounted for 2.7% and 3.0% of the total variances in the analyses of 0 versus 9%/sec fractional loss, and of constant-flow only, respectively. These effects are also illustrated in Figure 5.

Figure 7 also shows that longer core durations resulted in a longer mean reaction times for both constant-flow events and events with a 9%/sec fractional loss in flow rate. The main effect of core duration accounted for 6.8% of the total variance in the constant-flow only analysis, and 7.0% in the constant-flow versus 9%/sec fractional loss analysis.

Global optical texture density (which was constant within each event) showed an effect on correct-plus-error reaction times in the constant-flow versus 9%/sec fractional loss analysis, accounting for 2.1% of the total variance. Overall mean reaction times were 6.67, 6.66, and 6.63 sec for global optical texture densities of 2, 3, and 4.5 g/h, respectively. Corresponding correct-only mean reaction times were 6.79, 6.82, and 6.75 sec. From these values an inference may be made that the variability in the data is largely a result of error reaction times.

In summary, performance tended to be better as fractional loss in flow rate and global optical flow rate both assumed higher values. Longer core durations and the 5-sec initial duration also resulted in more accurate performance as indexed by both error rate and mean reaction time. Global optical texture density showed a minimal effect on performance.

### Discussion

Based on the results of the preliminary experiment, two subsequent experiments will be pursued in parallel: (1) an investigation of a broad range of initial durations, and (2) implementation of the originally planned factorial design contrasting potential optical sources of information for deceleration.

After initiating the preliminary experiment we discovered reports of an unpublished experiment by Denton (1973, Experiment 8; 1974, Experiment 7). Denton was interested in adaptation to speed during driving, and the unpublished experiment was the only one he conducted using a test for change in sensitivity to change in speed following a period of constant speed. He used initial constant-speed durations of 10 and 120 sec before initiating a constant deceleration of 10%/sec. Time to detect loss in speed increased with initial duration, in keeping with Denton's other adaptation findings. The effect is, however, opposite in direction and of much smaller magnitude than the decrease in detection time from 0 to 5 sec initial duration in our preliminary experiment. Since our effect cannot be explained by adaptation, there must be two phenomena involved. Therefore, one immediate follow-up experiment will explore the anticipated quadratic relationship over a broad range of initial constant-flow durations beginning with 0 sec and extending well into Denton's (1976) adaptation curve. Determining the form of this performance function is essential for optimizing our tests of sensitivity in any future study.

Denton (1973, 1974) also varied the speed during his initial durations from 5 to 80 mph (at an eyeheight of 4.5 ft, the flow rates ranged from 1.6 to 26.1 h/sec). As shown in Figure 8, detection time was highest for slow flow rates, dropping as

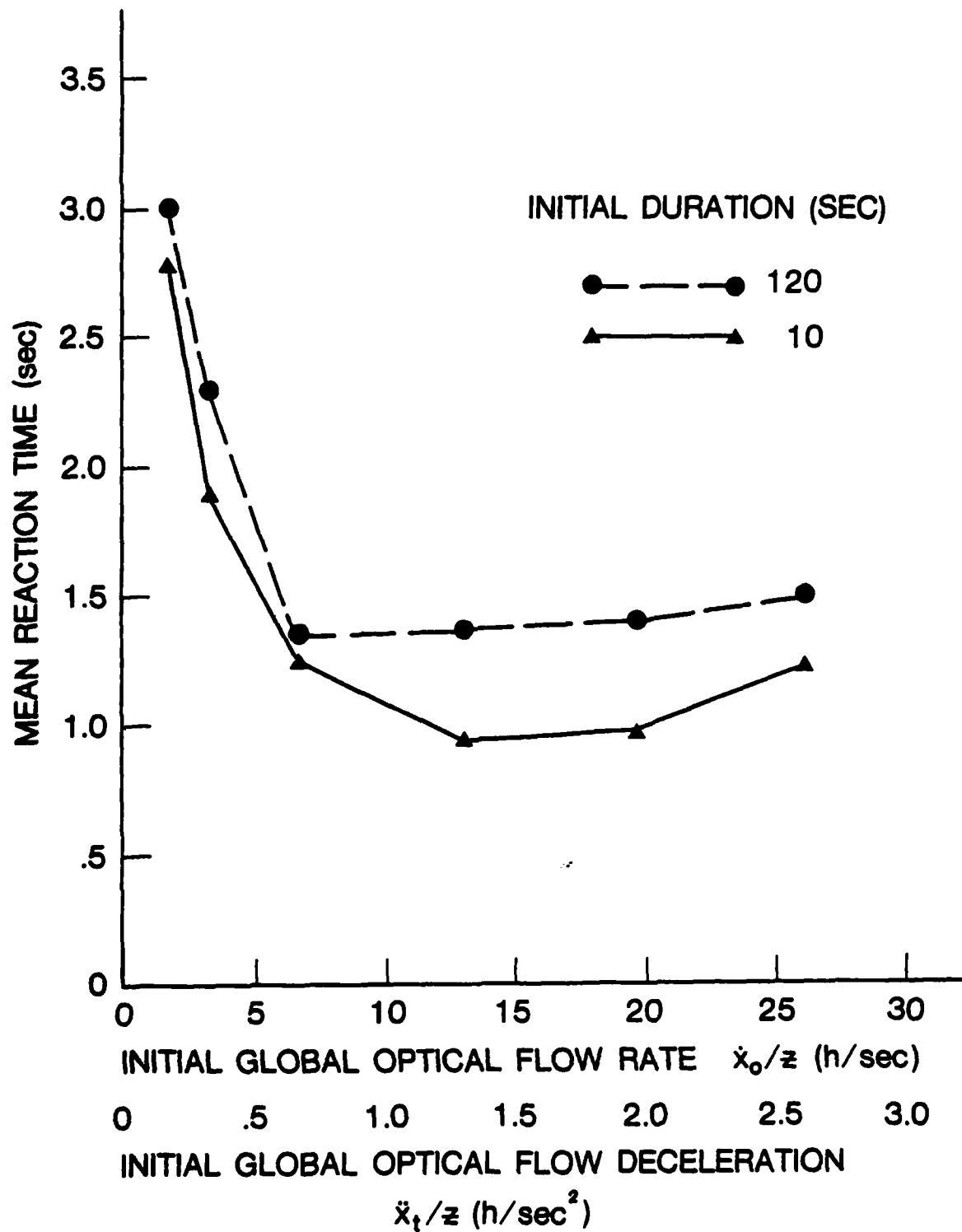


Figure 8. Mean time to detect deceleration as a function of initial duration and the combinations of flow rate and flow deceleration used to produce an initial fractional loss in flow rate of 10%/sec. Data from Experiment 8 (Denton, 1973).

flow rate increased, then rising slightly at the fastest rates. Two points are worth noting: (1) First, detection time varied radically with flow rate, even though fractional change in flow rate was exactly the same in every event. Our results suggest that a fractional loss of 10%/sec should be very easy to detect, yet Denton's detection times varied by 1.8 sec. There are, then, at least two optical-flow variables of importance in detecting change in self motion. Separation of their respective influences demands attention in a second follow-up experiment.

(2) Second, the flow rates we have been using are even below the lowest used by Denton. Since initiating this line of research, we have become increasingly concerned with the possibility that pilots may lose sensitivity to optical flow information as a function of adaptation to the high flow rates encountered during low-altitude flight. For example, at an operational speed of 450 kts (760 ft/sec), a pilot experiences a flow rate of 7.6 h/sec at an altitude of 100 ft. As shown in Figure 8, this value is approaching the region where sensitivity is greatest, but where the detrimental effect of adaptation is also greatest. This finding has implications for a pilot's ability to maintain a margin of safety. Since adaptation to flow may be a factor in near contact and collisions with the ground, it is important that higher flow rates be explored in our follow-up experiments.

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APPENDIX A

INVENTORIES OF EVENT AND PERFORMANCE VARIABLES

Table A-1

Inventory of Event and Performance Variables<sup>a</sup> for Experiment 1

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(\dot{x}/\dot{x})_t$	$\dot{x}_o/z$	$z/g$	$\dot{x}_o/g$	$\dot{x}_o$	$\ddot{x}_o$	$g$	$t_c$	$t_{I=0}$	$t_{I=0}$	$t_{I=0}$	$t_{I=0}$	$t_{I=5}$	$t_{I=5}$	$t_{I=5}$
Number								Pr Err	$\overline{RT}_c$	Conf	Pr Err	$\overline{RT}_c$	Conf	$\overline{RT}_c$
1	-.06	.4	2.0	.80	28	-1.68	35.00	10.0	.437	8.59	3.84	.562	5.47	3.25
2	-.06	.4	3.0	1.20	28	-1.68	23.33	10.0	.594	8.24	3.09	.562	5.86	3.28
3	-.06	.4	4.5	1.80	28	-1.68	15.56	10.0	.500	7.91	3.69	.531	6.03	3.47
4	-.06	.6	2.0	1.20	42	-2.52	35.00	10.0	.500	8.22	3.44	.562	6.31	3.28
5	-.06	.6	3.0	1.80	42	-2.52	23.33	10.0	.437	8.41	3.91	.562	7.19	3.25
6	-.06	.6	4.5	2.70	42	-2.52	15.56	10.0	.500	8.06	3.56	.500	7.10	3.44
7	-.06	.9	2.0	1.80	63	-3.78	35.00	10.0	.406	9.33	3.72	.562	6.77	3.28
8	-.06	.9	3.0	2.70	63	-3.78	23.33	10.0	.594	8.20	3.09	.469	7.21	3.56
9	-.06	.9	4.5	4.05	63	-3.78	15.56	10.0	.562	10.16	3.38	.562	6.05	3.34
10	-.09	.4	2.0	.80	28	-2.52	35.00	10.0	.500	7.33	3.53	.469	5.22	3.94
11	-.09	.4	3.0	1.20	28	-2.52	23.33	10.0	.500	6.65	3.41	.406	4.49	3.84
12	-.09	.4	4.5	1.80	28	-2.52	15.56	10.0	.656	7.13	3.13	.375	5.08	4.03
13	-.09	.6	2.0	1.20	42	-3.78	35.00	10.0	.500	7.19	3.47	.406	5.09	3.97
14	-.09	.6	3.0	1.80	42	-3.78	23.33	10.0	.625	8.42	3.16	.250	4.87	4.50

Table A-1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number	$(\ddot{x}/\dot{x})_t$	$\dot{x}_0/z$	$z/g$	$\dot{x}_0/g$	$\dot{x}_0$	$\dot{x}_0$	$g$	$t_c$	$t_{f=0}$	$RT_c$	$\overline{Conf}$	Pr Err	$\overline{RT_c}$	$t_{f=5}$
15	-.09	.6	4.5	2.70	42	-3.78	15.56	10.0	.469	7.10	3.56	.344	4.90	3.94
16	-.09	.9	2.0	1.80	63	-5.67	35.00	10.0	.531	7.85	3.34	.312	4.89	4.19
17	-.09	.9	3.0	2.70	63	-5.67	23.33	10.0	.531	8.25	3.44	.406	5.33	3.88
18	-.09	.9	4.5	4.05	63	-5.67	15.56	10.0	.437	6.72	3.59	.375	4.62	4.03
19	-.09	.4	2.0	.80	28	-2.52	35.00	7.5	.500	7.80	3.63	.250	5.43	4.50
20	-.09	.4	3.0	1.20	28	-2.52	23.33	7.5	.344	7.18	4.22	.344	5.75	4.16
21	-.09	.4	4.5	1.80	28	-2.52	15.56	7.5	.312	7.69	4.25	.187	5.59	4.53
22	-.09	.6	2.0	1.20	42	-3.78	35.00	7.5	.250	7.24	4.38	.344	6.28	4.09
23	-.09	.6	3.0	1.80	42	-3.78	23.33	7.5	.469	7.91	3.59	.281	6.48	4.41
24	-.09	.6	4.5	2.70	42	-3.78	15.56	7.5	.312	8.76	4.28	.312	6.40	4.16
25	-.09	.9	2.0	1.80	63	-5.67	35.00	7.5	.406	8.91	3.81	.469	6.14	3.53
26	-.09	.9	3.0	2.70	63	-5.67	23.33	7.5	.500	8.85	3.44	.250	5.71	4.44
27	-.09	.9	4.5	2.05	63	-5.67	15.56	7.5	.406	8.12	4.06	.344	5.93	4.25
28	-.09	.4	2.0	.80	28	-2.52	35.00	5.0	.562	9.01	3.19	.312	5.76	4.38
29	-.09	.4	3.0	1.20	28	-2.52	23.33	5.0	.375	9.01	3.97	.125	6.71	4.91

Table A-1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(\ddot{x}/\dot{x})_t$		$\dot{x}_0/z$	$z/g$	$\dot{x}_0/g$	$\dot{x}_0$	$\ddot{x}_0$	$g$	$t_c$	$t_i=0$	$t_i=0$	$t_i=0$	$t_i=5$	$t_i=5$	$t_i=5$
Number									Pr Err	$\overline{RT}_c$	Conf	Pr Err	$\overline{RT}_c$	Conf
30	-.09	.4	4.5	1.80	28	-2.52	15.56	5.0	.469	9.46	3.56	.500	6.26	3.59
31	-.09	.6	2.0	1.20	42	-3.78	35.00	5.0	.406	9.56	3.97	.250	6.59	4.56
32	-.09	.6	3.0	1.80	42	-3.78	23.33	5.0	.406	9.39	3.91	.375	6.39	3.97
33	-.09	.6	4.5	2.70	42	-3.78	15.56	5.0	.281	9.25	4.19	.250	6.57	4.59
34	-.09	.9	2.0	1.80	63	-5.67	35.00	5.0	.344	9.35	4.13	.156	6.45	4.91
35	-.09	.9	3.0	2.70	63	-5.67	23.33	5.0	.312	9.30	4.28	.312	6.37	4.22
36	-.09	.9	4.5	4.05	63	-5.67	15.56	5.0	.375	8.42	3.94	.156	6.67	4.88
37	-.135	.4	2.0	.80	28	-3.78	35.00	7.5	.344	8.18	4.25	.187	5.20	4.97
38	-.135	.4	3.0	1.20	28	-3.78	23.33	7.5	.281	8.65	4.56	.125	5.77	4.94
39	-.135	.4	4.5	1.80	28	-3.78	15.56	7.5	.250	7.49	4.50	.125	5.54	5.00
40	-.135	.6	2.0	1.20	42	-5.67	35.00	7.5	.469	7.23	3.59	.250	5.12	4.56
41	-.135	.6	3.0	1.80	42	-5.67	23.33	7.5	.125	8.04	4.94	.094	5.39	5.13
42	-.135	.6	4.5	2.70	42	-5.67	15.56	7.5	.188	7.87	4.81	.156	4.98	5.09
43	-.135	.9	2.0	1.80	63	-8.51	35.00	7.5	.500	8.42	3.59	.250	5.97	4.69
44	-.135	.9	3.0	2.70	63	-8.51	23.33	7.5	.312	7.39	4.25	.187	5.40	4.97

Table A-1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(\ddot{x}/\ddot{x})_t$		$\dot{x}_o/z$	$z/g$	$\dot{x}_o/g$	$\dot{x}_o$	$\ddot{x}_o$	$g$	$t_c$	$t_i=0$	$t_i=0$	$t_i=0$	$t_i=5$	$t_i=5$	$t_i=5$
Number									Pr Err	$\overline{RT}_c$	Conf	Pr Err	$\overline{RT}_c$	Conf
45	-.135	.9	4.5	4.05	63	-8.51	15.56	7.5	.437	7.75	3.84	.094	4.66	5.31
46	-.2025	.4	2.0	.80	28	-5.67	35.00	5.0	.250	6.77	4.34	.094	4.90	5.28
47	-.2025	.4	3.0	1.20	28	-5.67	23.33	5.0	.312	6.66	4.19	.156	4.89	4.78
48	-.2025	.4	4.5	1.80	28	-5.67	15.56	5.0	.219	6.30	4.75	.031	4.41	5.44
49	-.2025	.6	2.0	1.20	42	-8.51	35.00	5.0	.187	6.48	4.78	.219	4.50	4.81
50	-.2025	.6	3.0	1.80	42	-8.51	23.33	5.0	.344	6.72	4.22	.187	4.19	5.06
51	-.2025	.6	4.5	2.70	42	-8.51	15.56	5.0	.344	6.07	4.28	.187	4.21	5.22
52	-.2025	.9	2.0	1.80	63	-12.76	35.00	5.0	.344	6.26	4.28	.094	4.05	5.28
53	-.2025	.9	3.0	2.70	63	-12.76	23.33	5.0	.281	6.24	4.25	.125	4.04	5.13
54	-.2025	.9	4.5	4.05	63	-12.76	15.56	5.0	.375	6.92	4.19	.031	3.98	5.56
55	0	.4	2.0	.80	28	0	35.00	5.0	.344	5.97	2.81	.219	5.45	2.52
56	0	.4	3.0	1.20	28	0	23.33	5.0	.312	6.16	2.78	.250	5.53	2.59
57	0	.4	4.5	1.80	28	0	15.56	5.0	.391	6.13	3.23	.250	5.37	2.50
58	0	.6	2.0	1.20	42	0	35.00	5.0	.250	6.13	2.55	.125	5.43	2.27
59	0	.6	3.0	1.80	42	0	23.33	5.0	.360	6.14	3.05	.125	5.16	2.08

Table A-1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(\dot{x}/x)_t$		$\dot{x}_0/z$	$z/g$	$\dot{x}_0/g$	$\dot{x}_0$	$\ddot{x}_0$	$g$	$t_c$	$t_i=0$	$t_i=0$	$t_i=0$	$t_i=5$	$t_i=5$	$t_i=5$
Number									Pr Err	$\overline{RT}_c$	Conf	Pr Err	$\overline{RT}_c$	Conf
60	0	.6	4.5	2.70	42	0	15.56	5.0	.219	5.79	2.64	.094	5.22	1.72
61	0	.9	2.0	1.80	63	0	35.00	5.0	.156	5.60	2.06	.172	5.05	2.02
62	0	.9	3.0	2.70	63	0	23.33	5.0	.234	5.82	2.55	.094	5.17	1.86
63	0	.9	4.5	4.05	63	0	15.56	5.0	.110	5.79	1.86	.110	4.99	2.00
64	0	.4	2.0	.80	28	0	35.00	7.5	.328	7.30	2.84	.219	6.64	2.44
65	0	.4	3.0	1.20	28	0	23.33	7.5	.375	7.66	3.05	.219	6.39	2.48
66	0	.4	4.5	1.80	28	0	15.56	7.5	.328	8.27	2.91	.141	6.50	2.09
67	0	.6	2.0	1.20	42	0	35.00	7.5	.234	7.72	2.50	.125	6.47	2.09
68	0	.6	3.0	1.80	42	0	23.33	7.5	.234	7.56	2.30	.219	6.34	2.47
69	0	.6	4.5	2.70	42	0	15.56	7.5	.141	7.29	2.06	.156	6.05	2.13
70	0	.9	2.0	1.80	63	0	35.00	7.5	.156	7.41	2.03	.110	5.89	1.69
71	0	.9	3.0	2.70	63	0	23.33	7.5	.156	6.76	1.98	.141	6.06	1.80
72	0	.9	4.5	4.05	63	0	15.56	7.5	.187	6.95	2.13	.078	5.71	1.75
73	0	.4	2.0	.80	28	0	35.00	10.0	.250	8.38	2.58	.250	7.02	2.55
74	0	.4	3.0	1.20	28	0	23.33	10.0	.250	8.88	2.48	.187	7.16	2.30

Table A-1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$(\dot{x}/x)_t$	$\dot{x}_o/z$	$z/g$	$\dot{x}_o/g$	$\dot{x}_o$	$\ddot{x}_o$	g	$t_c$	$t_{f=0}$	$t_{f=0}$	$t_{f=0}$	$t_{f=0}$	$t_{f=5}$	$t_{f=5}$	$t_{f=5}$
Number								Pr Err	RT <sub>c</sub>	Conf	Pr Err	RT <sub>c</sub>	Conf	Conf
75	0	.4	4.5	1.80	28	0	15.56	10.0	.391	8.93	3.00	.234	7.22	2.36
76	0	.6	2.0	1.20	42	0	35.00	10.0	.281	9.02	2.58	.172	6.89	2.13
77	0	.6	3.0	1.80	42	0	23.33	10.0	.141	8.21	2.05	.125	7.12	2.00
78	0	.6	4.5	2.70	42	0	15.56	10.0	.156	8.74	2.06	.141	7.26	2.06
79	0	.9	2.0	1.80	63	0	35.00	10.0	.172	7.90	2.09	.047	6.85	1.44
80	0	.9	3.0	2.70	63	0	23.33	10.0	.141	8.06	1.92	.125	6.38	1.84
81	0	.9	4.5	4.05	63	0	15.56	10.0	.156	8.47	1.97	.062	6.46	1.55

a Variables1.  $(\dot{x}/\dot{x})_t$  = fractional loss in speed and flow rate (pr eyeheight/sec).2.  $\dot{x}_o/z$  = initial global optical flow rate (eyeheight/sec).3.  $z/g$  = global optical density (ground units/eyeheight).4.  $\dot{x}_o/g$  = initial edge rate (ground units or edges/sec).5.  $\dot{x}_o$  = initial forward velocity (m/sec).6.  $\ddot{x}_o$  = initial decleration rate (m/sec<sup>2</sup>).

7. g = ground texture unit size (m).

8.  $t_c$  = core duration (sec).

Table A-1, continued

9., 10., 11., 12., 13., 14.  $t_i$  = initial duration (sec).

9., 12. Pr Err = proportional error.

10, 13.  $\overline{RT}_c$  = mean reaction time for current responses (sec).

11., 14. Conf = mean confidence rating converted to a 6-point scale (1 = "very certain constant" to

6 = "very certain decelerating").

Note: A dot over a symbol indicates a derivative with respect to time. A subscript of zero

indicates the value of a variable at the initiation of an event, while a subscript of  $t$

indicates the value of a variable at any time during the event.

APPENDIX B  
INSTRUCTIONS

## INSTRUCTIONS

## Experiment 1

All Subjects:

Welcome to the Aviation Psychology Laboratory. We conduct research which deals with perceptual factors in aviation. In this experiment, we are interested in your sensitivity to decrease in traveling speed. We want to find out how well you can visually detect deceleration, in the absence of motion cues such as the feeling of being pushed forward in your seat as a car you are riding in decelerates.

You will be shown computer-generated scenes on the screen which represent forward travel in an airplane over open, flat farmlands. Your speed will be constant in some scenes, and will decelerate in others. Your task will be to press the button labeled "C" if you believe the scene represents constant speed, or press the button labeled "D" if you believe the scene is slowing down, or decelerating.

The size of the simulated fields will vary from scene to scene as will the speed and duration of your simulated travel. No matter how fast or slow the speed, how long or short the scene, or how dense or sparse the fields appear, you should base your judgments only on whether you see deceleration or constant speed over the course of the single scene.

Sometimes you may notice a shimmering of the fields along the horizon. This effect is due to limitations of our equipment; please ignore it.

Odd-Numbered Subjects:

The specific procedure is:

- (1) Before the beginning of each scene, I will say "ready". Turn your full attention to the screen then.
- (2) A scene representing either constant or decelerating speed will appear. The scene may last anywhere from 5 to 10 seconds.
- (3) As soon as you can distinguish which type of motion is represented, press the button corresponding to your choice ("D" or "C"). You do not have to wait until the end of the scene to press the button, but a judgment must be made for each scene.
- (4) After you press the button, rate your confidence in your accuracy by saying "one" if you guessed, "two" if you are fairly certain, or "three" if you are very certain of your answer.
- (5) Prior to the actual experiment, you will be shown nine practice scenes, to be sure you fully understand the procedure. Then you will be shown a total of 216 scenes, with a short rest break after each set of 54.

Do you have any questions?

After 108 scenes:

The procedure for the second 108 scenes will be the same as before, but with a slight modification. After I say "ready", a scene will appear, but it will always begin with a 5-second period of constant travel. After the 5 seconds, you will hear a signal. After this tone, the scene may continue at a constant speed or begin to decelerate. The scene may last anywhere from an additional 5 to 10 seconds after the signal. As soon as you can distinguish which type of travel is represented, respond as you did before by pressing the button and rating your confidence. Again, you do not have to wait until the end of the scene to press the button. We will begin with 9 practice scenes. Do you have any questions?

Even-Numbered Subjects:

The specific procedure is:

- (1) Before the beginning of each scene, I will say "ready". Turn your full attention to the screen then.
- (2) A scene beginning with 5 seconds of constant travel will appear. After the five seconds, you will hear a signal. After this tone, the scene may continue at a constant speed, or begin to decelerate. The scene could last anywhere from an additional 5 to an additional 10 seconds after the signal.
- (3) As soon after the tone as you can distinguish which type of option is represented, press the button corresponding to your choice ("D" or "C"). You do not have to wait until the end of the scene to press the button, but a judgment must be made for each scene.
- (4) After you press the button, rate your confidence in your accuracy by saying "one" if you guessed, "two" if you are fairly certain, or "three" if you are very certain of your answer.
- (5) Prior to the actual experiment, you will be shown nine practice scenes, to be sure you fully understand the procedure. Then you will be shown a total of 216 scenes, with a short rest after each set of 54.

Do you have any questions?

After 108 scenes:

The procedure for the second 108 scenes will be the same as before, but with a slight modification. After I say "ready", a scene will appear, but it will not be preceded by a 5-second period of constant travel. If the scene represents constant travel, it will remain constant; if the scene represents decelerating travel, it will begin to slow down immediately. As soon as you can distinguish

which type of travel is represented, respond as you did before, by pressing the button and rating your confidence. Again, you do not have to wait until the end of the scene to press the button. The scenes may last anywhere from 5 to 10 seconds. We will begin with 9 practice scenes. Do you have any questions?

APPENDIX C

ANALYSIS OF VARIANCE SUMMARY TABLES

Table C-1

## 5-Sec Core Duration Decelerating Events - Proportion Errors

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	16.531	6.5	56.90	.0000
Initial Optical Flow Rate (O)	2	.064	0.0	.13	.8819
Global Optical Texture Density (D)	2	.116	0.0	.35	.7079
Initial Duration (I)	1	7.670	3.0	16.71	.0003
FO	2	.724	0.3	3.07	.0538
FD	2	.068	0.0	.20	.8171
FI	1	.014	0.0	.08	.7823
OD	4	.019	0.0	.03	.9981
OI	2	.127	0.0	.45	.6415
DI	2	.283	0.1	.86	.4288
FOD	4	.693	0.3	.91	.4577
FOI	2	.585	0.2	1.84	.1675
FDI	2	.158	0.1	.47	.6297
ODI	4	1.092	0.4	1.41	.2351
FODI	4	.634	0.2	.95	.4382
Pooled Error	1116	225.873	88.9	-	-
Total	1151	254.651	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-2

## 5-Sec Core Duration Decelerating Events - Mean Reaction Time

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	120.075	2.3	54.81	.0000
Initial Optical Flow Rate (O)	2	12.282	0.2	5.25	.0079
Global Optical Texture Density (D)	2	13.260	0.3	4.90	.0106
Initial Duration (I)	1	950.180	18.4	29.23	.0000
FO	2	8.411	0.2	3.98	.0239
FD	2	.058	0.0	.11	.8971
FI	1	.753	0.0	.46	.5007
OD	4	1.691	0.0	.30	.8790
OI	2	6.087	0.1	1.76	.1806
DI	2	.733	0.0	.36	.6978
FOD	4	10.565	0.2	2.24	.0683
FOI	2	5.717	0.0	2.59	.0834
FDI	2	2.007	0.0	1.27	.2886
ODI	4	12.319	0.2	2.55	.0428
FODI	4	6.799	0.1	1.20	.3164
Pooled Error	1116	4022.055	78.0	-	-
Total	1151	5172.992	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-3

## 7.5-Sec Core Duration Decelerating Events - Proportion Errors

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	3.230	1.3	14.07	.0008
Initial Optical Flow Rate (O)	2	1.460	0.6	2.94	.0604
Global Optical Texture Density (D)	2	1.825	0.8	4.65	.0132
Initial Duration (I)	1	4.133	1.7	13.34	.0010
FO	2	.012	0.0	.03	.9666
FD	2	.950	0.4	3.01	.0569
FI	1	.459	0.2	2.21	.1474
OD	4	.160	0.1	.23	.9222
OI	2	.505	0.2	2.08	.1340
DI	2	.005	0.0	.02	.9817
FOD	4	.972	0.4	1.33	.2614
FOI	2	.231	0.1	.59	.5562
FDI	2	.595	0.2	1.76	.1803
ODI	4	.615	0.3	1.13	.3459
FODI	4	1.503	0.6	1.75	.1435
Pooled Error	1116	223.406	93.1	-	-
Total	1151	240.061	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-4

## 7.5-Sec Core Duration Decelerating Events - Mean Reaction Time

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	25.723	0.3	4.27	.0474
Initial Optical Flow Rate (O)	2	15.886	0.2	2.17	.1225
Global Optical Texture Density (D)	2	11.838	0.1	2.22	.1179
Initial Duration (I)	1	1094.200	12.6	30.56	.0000
FO	2	6.033	0.1	.86	.4297
FD	2	.201	0.0	.04	.9568
FI	1	4.965	0.1	2.00	.1680
OD	4	34.429	0.4	3.20	.0156
OI	2	3.999	0.0	.56	.5740
DI	2	2.566	0.0	.51	.6029
FOD	4	.530	0.0	.06	.9942
FOI	2	41.842	0.5	5.72	.0053
FDI	2	.171	0.0	.05	.9521
ODI	4	9.648	0.1	.75	.5587
FODI	4	6.738	0.1	.71	.5874
Pooled Error	1116	7419.231	85.5	-	-
Total	1151	8678.883	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-5

## 10-Sec Core Duration Decelerating Events - Proportion Errors

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	10.503	3.7	42.85	.0000
Initial Optical Flow Rate (O)	2	.724	0.3	1.40	.2552
Global Optical Texture Density (D)	2	.021	0.0	.06	.9465
Initial Duration (I)	1	.500	0.2	1.19	.2839
FO	2	.585	0.2	1.68	.1956
FD	2	.132	0.0	.31	.7350
FI	1	1.836	0.7	7.38	.0108
OD	4	.958	0.3	1.12	.3511
OI	2	.193	0.1	.48	.6220
DI	2	.021	0.0	.05	.9507
FOD	4	1.951	0.7	2.64	.0369
FOI	2	.054	0.0	.14	.8657
FDI	2	.840	0.3	2.40	.0996
ODI	4	.740	0.3	1.00	.4125
FODI	4	.816	0.3	.89	.4705
Pooled Error	1116	261.991	92.9	-	-
Total	1151	281.865	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-6

## 10-Sec Core Duration Decelerating Events - Mean Reaction Time

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	.937	0.0	.07	.7865
Initial Optical Flow Rate (O)	2	10.965	0.1	1.30	.2798
Global Optical Texture Density (D)	2	4.989	0.0	.60	.5501
Initial Duration (I)	1	1212.681	15.7	40.49	.0000
FO	2	4.751	0.0	.38	.6883
FD	2	5.874	0.0	.74	.4837
FI	1	11.312	0.1	2.62	.1157
OD	4	1.814	0.0	.11	.9788
OI	2	8.355	0.1	1.07	.3511
DI	2	1.983	0.0	.25	.7832
FOD	4	42.316	0.5	2.21	.0723
FOI	2	11.563	0.2	1.64	.2018
FDI	2	4.548	0.0	.64	.5334
ODI	4	4.688	0.0	.36	.8378
FODI	4	35.207	0.5	2.04	.0927
Pooled Error	1116	6340.218	82.8	-	-
Total	1151	7702.201	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-7

## Constant-Speed Versus 9%/sec Fractional Loss

## in Flow Rate - Proportion Errors

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	27.896	4.7	22.08	.0001
Initial Optical Flow Rate (O)	2	4.587	0.8	16.23	.0000
Global Optical Texture Density (D)	2	.240	0.0	.86	.4289
Initial Duration (I)	1	8.912	1.5	36.79	.0000
Core Duration (C)	2	3.469	0.6	9.40	.0003
FO	2	1.723	0.3	2.04	.1389
FD	2	.025	0.0	.06	.9388
FI	1	.269	0.0	.61	.4399
FC	2	1.462	0.2	3.30	.0436
OD	4	1.222	0.2	2.08	.0875
OI	2	.238	0.0	.94	.3951
OC	4	1.052	0.2	2.54	.0431
DI	2	.058	0.0	.22	.8067
DC	4	.603	0.1	1.28	.2804
IC	2	.372	0.1	1.75	.1827
FOD	4	.365	0.1	.72	.5830
FOI	2	.064	0.0	.24	.7837
FOC	4	.767	0.1	1.48	.2139
ODI	4	.475	0.1	.86	.4898
ODC	8	1.824	0.3	1.84	.0706
DIC	4	.618	0.1	1.25	.2921
FDI	2	.126	0.0	.41	.6633

Table C-7, continued

Source	DF	SS	R <sup>2</sup> %	F	p<F
FDC	4	.086	0.0	.18	.9490
FIC	2	.149	0.0	.38	.6869
OIC	4	.874	0.1	1.52	.2019
FODI	4	.459	0.1	1.03	.3958
FODC	8	.909	0.2	.91	.5062
FOIC	4	.073	0.0	.14	.9657
FDIC	4	.376	0.1	.91	.4592
ODIC	8	1.757	0.3	1.74	.0906
FODIC	8	2.108	0.4	2.03	.0440
Pooled Error	3348	534.139	89.4	-	-
Total	3455	597.294	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-8  
 Constant-Speed Versus 9%/sec Fractional Loss  
 in Flow Rate - Mean Reaction Time

Source	DF	SS	R <sup>2</sup> %	F	p<F
Fractional Loss in Flow Rate (F)	1	17.711	0.0	1.65	.2083
Initial Optical Flow Rate (O)	2	39.014	0.2	6.45	.0029
Global Optical Texture Density (D)	2	496.215	2.1	22.02	.0000
Initial Duration (I)	1	632.380	2.7	33.02	.0000
Core Duration (C)	2	1634.865	7.0	50.43	.1539
FO	2	11.017	0.0	1.93	.1534
FD	2	544.764	2.3	29.11	.0000
FI	1	39.786	0.2	5.39	.0273
FC	2	49.268	0.2	7.22	.0016
OD	4	9.972	0.0	1.37	.2482
OI	2	4.701	0.0	1.12	.3328
OC	4	14.356	0.1	1.59	.1803
DI	2	145.451	0.6	16.34	.0000
DC	4	8.203	0.0	.91	.4627
IC	2	16.603	0.1	3.23	.0466
FOD	4	5.660	0.0	.61	.6537
FOI	2	2.917	0.0	.55	.5826
FOC	4	3.315	0.0	.32	.8616
ODI	4	12.167	0.1	1.40	.2392
ODC	8	29.466	0.1	1.73	.0920
DIC	4	5.302	0.0	.78	.5406
FDI	2	118.306	0.5	13.88	.0000

Table C-8, continued

Source	DF	SS	R <sup>2</sup> %	F	p<F
FDC	4	3.057	0.0	.34	.8528
FIC	2	17.577	0.1	3.12	.0513
OIC	4	3.387	0.0	.40	.8108
FODI	4	.736	0.0	.08	.9874
FODC	8	24.059	0.1	1.87	.0658
FOIC	4	2.936	0.0	.41	.8028
FDIC	4	4.764	0.0	.72	.5797
ODIC	8	34.911	0.2	2.12	.0347
FODIC	8	7.940	0.0	.56	.8117
Pooled Error	3348	19,273.488	83.4	-	-
Total	3455	23,214.294	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-9

## Constant-Speed Events - Proportion Errors

Source	DF	SS	R <sup>2</sup> %	F	p<F
Initial Optical Flow Rate (O)	2	11.724	2.1	16.02	.0000
Global Optical Texture Density (D)	2	.231	0.0	.74	.4806
Initial Duration (I)	1	6.084	1.1	11.46	.0020
Core Duration (C)	2	.502	0.1	1.73	.1856
Repetitions (R)	1	.354	0.0	1.81	.1889
OD	4	.681	0.1	1.55	.1922
OI	2	.393	0.0	1.00	.3745
OC	4	.040	0.0	.07	.9906
OR	2	.150	0.0	.60	.5505
DI	2	.018	0.0	.06	.9406
DC	4	.767	0.1	1.49	.2088
DR	2	.008	0.0	.02	.9779
IC	2	.212	0.0	.84	.4384
IR	1	.153	0.0	.98	.3292
CR	2	.268	0.0	.94	.3959
ODI	4	.633	0.1	1.12	.3521
ODC	8	1.139	0.2	1.10	.3655
ODR	4	1.241	0.2	2.03	.0948
DIC	4	.470	0.1	.98	.4195
DIR	2	.556	0.1	1.95	.1515
ICR	2	.449	0.1	2.40	.0990
OIC	4	1.069	0.2	2.11	.0841
OIR	2	.101	0.0	.40	.6700

Table C-9, continued

Source	DF	SS	R <sup>2</sup> %	F	p<F
OCR	4	.329	0.0	.68	.6092
DCR	4	.352	0.0	.71	.5860
ODIC	8	1.020	0.2	1.06	.3896
ODIR	4	.828	0.2	1.52	.2011
ODCR	8	1.166	0.2	1.26	.2655
OICR	4	.305	0.0	.68	.6075
DICR	4	.480	0.0	.98	.4186
ODICR	8	1.433	0.3	1.57	.1341
Pooled Error	3348	513.663	94.6	-	-
Total	3455	546.819	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table C-10

## Constant-Speed Events - Mean Reaction Time

Source	DF	SS	R <sup>2</sup> %	F	p<F
Initial Optical Flow Rate (O)	2	89.632	0.3	12.53	.0000
Global Optical Texture Density (D)	2	2.199	0.0	.40	.6737
Initial Duration (I)	1	989.403	3.0	24.39	.0000
Core Duration (C)	2	2251.623	6.8	55.59	.0000
Repetitions (R)	1	2.067	0.0	.35	.5597
OD	4	8.003	0.0	.98	.4236
OI	2	13.181	0.0	3.35	.0416
OC	4	15.312	0.0	1.39	.2431
OR	2	.368	0.0	.11	.8960
DI	2	6.529	0.0	1.68	.1944
DC	4	19.076	0.1	2.00	.0993
DR	2	1.643	0.0	.53	.5889
IC	2	68.122	0.2	5.04	.0095
IR	1	3.089	0.0	.63	.4346
CR	2	17.217	0.1	6.09	.0039
ODI	4	16.948	0.1	1.99	.1000
ODC	8	14.434	0.0	.86	.5547
ODR	4	6.128	0.0	.62	.6469
DIC	4	7.157	0.0	.93	.4501
DIR	2	8.049	0.0	1.34	.2699
ICR	2	7.030	0.0	2.06	.1368
OIC	4	1.921	0.0	.20	.9370
OIR	2	.748	0.0	.16	.8530

Table C-10, continued

Source	DF	SS	R <sup>2</sup> %	F	p<F
OCR	4	6.645	0.0	.81	.5239
DCR	4	3.808	0.0	.44	.7774
ODIC	8	33.518	0.1	2.01	.0461
ODIR	4	12.559	0.0	1.58	.1832
ODCR	8	28.766	0.1	1.79	.0799
OICR	4	.431	0.0	.05	.9955
DICR	4	5.412	0.0	.57	.6814
ODICR	8	12.296	0.0	.74	.6565
Pooled Error	3348	29,398.670	89.2	-	-
Total	3455	33,051.984	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

EXPERIMENT 2

THE FUNCTIONAL UTILITY OF OPTICAL FLOW ACCELERATION  
AS INFORMATION FOR DETECTING LOSS IN ALTITUDE

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Abstract

Optical analyses have identified three kinds of global flow-pattern information for detection of loss in one's own altitude: (1) optical flow acceleration, (2) decrease in optical texture density, and (3) increase in optical (perspectival) splay angle. An experiment was conducted contrasting constant descent rates which produced optical acceleration, with decreasing descent rates which produced constant optical flow. As found in earlier studies, observers were very sensitive to fractional loss in altitude. Eliminating optical flow acceleration, however, had little effect on an observers' detection of loss in altitude, indicating that changes in optical splay and/or optical texture density must be the salient sources of information. Varying initial texture density and event duration had no substantial effects on detection of descent.

Introduction

Gibson (1958) identified two types of optical information which accompany loss in altitude: (1) optical magnification of surface texture elements and (2) acceleration of the flow of optical texture discontinuities. He noted that "approach to a solid surface is specified by a centrifugal flow of the texture of the optic array. . . . A uniform

rate of approach is accompanied by an accelerated rate of magnification (p. 188)."

One of the goals of our research is to isolate optical variables as potential sources of information about self motion in order to test their perceptual effectiveness. Since optical variables specify the relationship between self motion along the path of observation and surfaces of the environment with respect to which an individual is moving, optical control is achieved by manipulating the direction and speed of self motion and the characteristics of surface texture. By following this strategy for optical analysis, three global optical variables have been identified mathematically which might serve as information for detecting loss in one's own altitude above the ground: (1) optical flow acceleration, (2) decrease in optical texture density, and (3) increase in optical (perspectival) splay angle.

The purpose of the current experiment was to assess the usefulness of flow acceleration by contrasting sensitivity to loss in altitude under conditions which produce or eliminate flow acceleration. If flow acceleration was the only useful information for distinguishing descent from level self motion, performance would be at chance level in its absence.

Given path speed ( $\dot{s}$ ) and altitude ( $z$ ), global optical flow rate can be specified by  $\dot{s}/z$ , since this ratio is a multiplier on every flow vector in the optic array (Gibson, Olum, & Rosenblatt, 1955; Warren, 1982). Hence, global flow rate varies with change in speed and/or altitude. The following general formula expresses this variation:

$$\text{Global optical flow acceleration} = \frac{\ddot{s}}{z} - \left( \frac{\dot{s}}{z} \right) \left( \frac{\dot{z}}{z} \right) \quad (1)$$

(where  $\ddot{s}$  = path speed acceleration, and  $\dot{z}$  = rate of change in altitude).

When path speed is constant ( $\dot{s} = 0$ ) during descent along a linear path, the equation simplifies to express an exponentially increasing flow rate. If path speed and sink rate are decreased at exactly the rate necessary to make the two terms in Equation 1 cancel, optical flow rate will be held constant, and flow rate acceleration will be eliminated as information for descent. (To remain on a linear path,  $\dot{s}$ ,  $\dot{z}$ , and  $\dot{x}$  (ground speed) must all decrease at the same rate.)

Elimination of flow rate acceleration can be accomplished by application of the following formulae:

$$\dot{x}_t = \dot{x}_0 e^{(\dot{z}_0/z_0)t} \quad (2)$$

(where  $\dot{x}_t$  = forward speed at time  $t$ ,  $\dot{x}_0$  = initial forward speed,  $e = 2.718$ ,  $\dot{z}_0$  = initial descent rate, and  $z_0$  = initial altitude), and

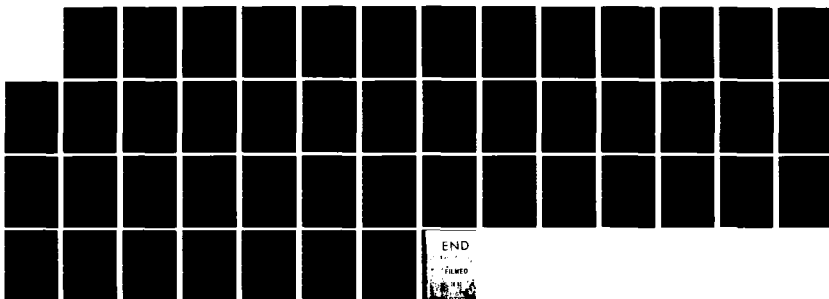
$$\dot{z}_t = \dot{z}_0 e^{(\dot{z}_0/z_0)t} \quad (3)$$

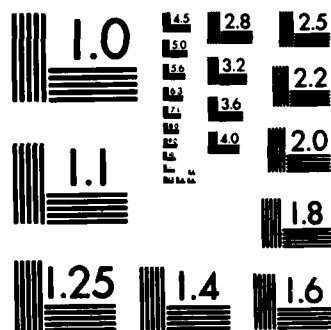
(where  $\dot{z}_t$  = descent rate at time  $t$ ). Initial path speed ( $\dot{s}_0$ ) and path speed at time  $t$  ( $\dot{s}_t$ ) will be completely determined by and take the same form as did  $\dot{x}$  and  $\dot{z}$  in formulae (2) and (3), respectively.

If descent is distinguishable in the absence of flow acceleration, observers must be sensitive to one or more of the other optical variables specifying loss in altitude. Increase in global splay angle and decrease in optical texture density (which is inversely related to optical magnification) are treated in a subsequent study by Wolpert, Owen, and Warren (Experiment 3, this report).

In light of the finding in an earlier experiment (Owen, Warren, & Mangold, in press) indicating that observers were sensitive to fractional

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loss in altitude ( $\dot{z}/z$ ), rather than descent rate per se, it is important to note that when flow rate is held constant, fractional loss is also constant over the duration of the event. As shown in Figure 1, a constant path speed produces an increase in the value of flow rate and fractional loss in altitude, whereas an exponentially decreasing path speed produces constant values for both. If observers are sensitive to either flow acceleration or the optical specifiers of fractional loss in altitude, it is reasonable to expect that performance will be more accurate and efficient when the value increases over time than when it has the same initial value, but is invariant over time.

Although our controls were implemented for theoretical reasons, it should be noted that the nature of the events simulated differs for the two types of conditions investigated. Approach to a surface by a fixed-wing aircraft typically approximates a constant path speed, resulting in flow acceleration. In contrast, deceleration on the path slope is a typical landing approach for helicopters, and not unusual for vertical/short take-off and landing aircraft (Hennessey, Sullivan, & Cooles, 1980).

### Method

#### Design

Four independent variables were orthogonally crossed in this study: (1) three levels of global optical flow rate ( $\dot{s}/z$ ), at .25, .50, and 1.00 h/sec (where h = eyeheight), to investigate its effects when held constant throughout a descent event; (2) four levels of fractional loss in altitude, at 0, 1.5, 3.0, and 6.0 %/sec, to investigate the salience of change in optical splay and optical texture density as information for descent when varied independently of flow rate; (3) two values of

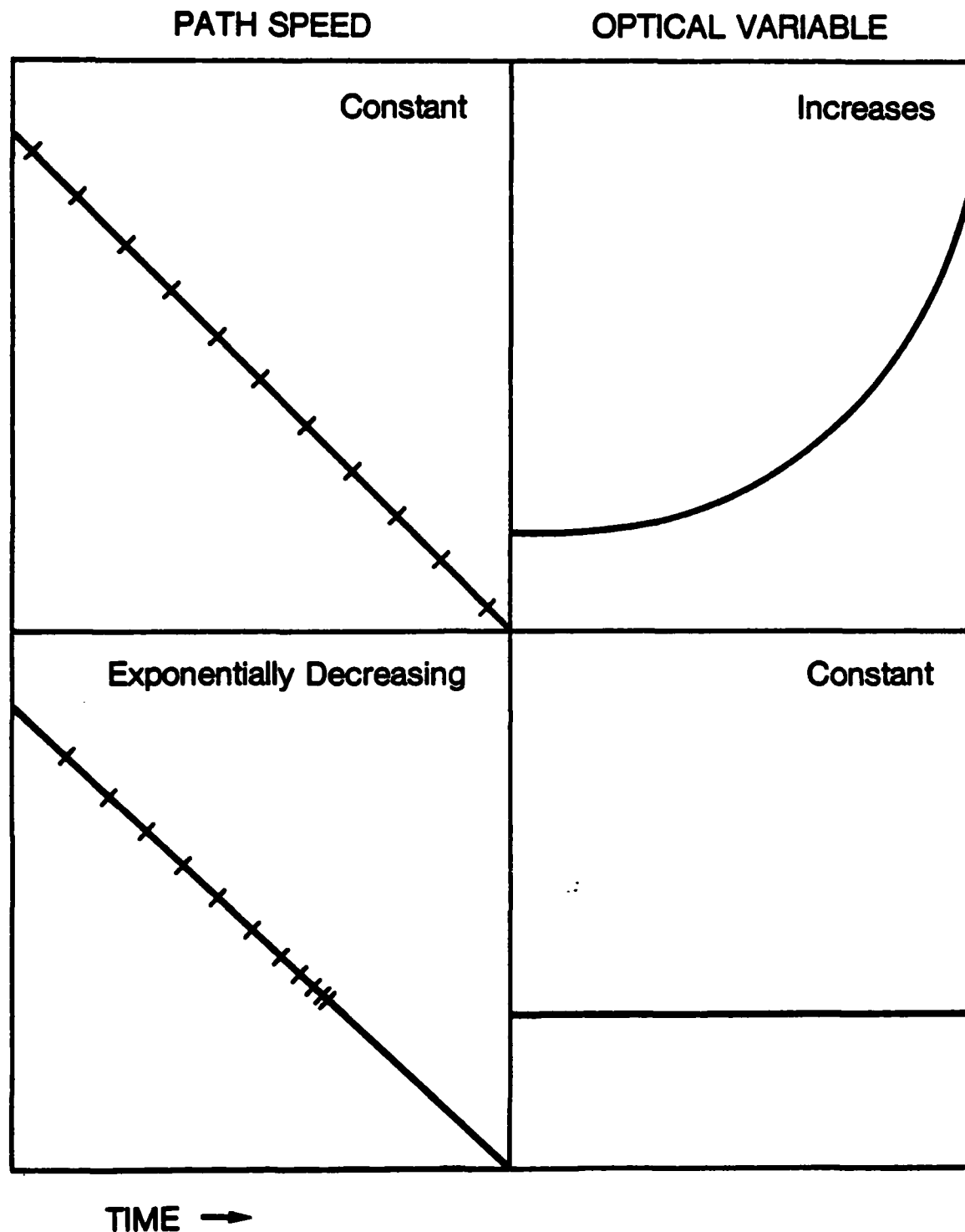


Figure 1. The relationship of path speed to fractional loss in altitude and its global optical specifiers: fractional increase in optical flow rate, splay rate, and fractional decrease in optical density. The hash marks indicate position along the path of locomotion for each consecutive unit of time.

optical texture density ( $z/g$ ), at 2 and 4 g/h, to determine whether the density of texture elements has any effect on sensitivity to loss in altitude; and (4) three different event durations, at 2, 4, and 8 sec, to assess the effect of speed stress on the detection of descent.

A single starting altitude of 72 m was used throughout the experiment. An inventory of optical and environmental variables for the events produced by the above crossings is presented in Table 1. Levels of the optical variables were chosen on the basis of a preliminary experiment (Hettinger, 1981; Hettinger, Warren, & Owen, 1982).

In addition to these independent variables, four basic conditions, or cases, were included in the design.

Case 1: Level flight with constant optical flow.

Case 2: Descent with increasing optical flow.

Case 3: Level flight with decreasing optical flow.

Case 4: Descent with constant optical flow.

Cases 2 and 4 constitute the main contrast of interest in the study: descent with versus without optical flow acceleration. Cases 1 and 3 afford an opportunity to investigate the effects of varying optical flow conditions on the detection of level flight, while also serving as "catch" trials for the descent events. Path speed was constant in Case 1; decelerating in Case 3. Cases 1 and 2 were matched in terms of path speed, as were Cases 3 and 4.

#### Apparatus

The simulated flight events were generated by a PDP 11/34 computer and a special-purpose scene generator in real time, and displayed via a Sony model KP-7200 video projection unit having a screen 1.5 m wide and

Table 1

Inventory of Displayed Events and Mean Performance Variables<sup>a</sup>

Event	1	2	3	4	5	6	7	8	9	10	11	12	13
Number	$\dot{z}_o/z$	$\dot{s}_o/z$	$z_o/g$	$z_o$	$\dot{z}_o$	$\dot{s}_o$	$g$	$\dot{s}_o/g$	$\dot{z}_o/g$	$(\dot{z}/\dot{x})_t$	Pr Err	$\overline{RT}_c$	Conf
1	0	.25	2	72	0	18	36	.50	0	0	.131	3.469	2.44
2	0	.25	4	72	0	18	18	1.00	0	0	.163	3.338	2.47
3	0	.50	2	72	0	36	36	1.00	0	0	.122	3.206	2.45
4	0	.50	4	72	0	36	18	2.00	0	0	.155	3.302	2.52
5	0	1.00	2	72	0	72	36	2.00	0	0	.134	3.083	2.51
6	0	1.00	4	72	0	72	18	4.00	0	0	.222	3.157	2.47
7	-.015	.25	2	72	-1.08	18	36	.50	-.03	-.06	.440	4.160	2.13
8	-.015	.25	4	72	-1.08	18	18	1.00	-.06	-.06	.389	3.808	2.21
9	-.015	.50	2	72	-1.08	36	36	1.00	-.03	-.03	.657	4.027	2.30
10	-.015	.50	4	72	-1.08	36	18	2.00	-.06	-.03	.551	3.630	2.22
11	-.015	1.00	2	72	-1.08	72	36	2.00	-.03	-.02	.713	4.114	2.36
12	-.015	1.00	4	72	-1.08	72	18	4.00	-.06	-.02	.657	3.889	2.36
13	-.03	.25	2	72	-2.16	18	36	.50	-.06	-.12	.162	2.658	2.65
14	-.03	.25	4	72	-2.16	18	18	1.00	-.12	-.12	.116	2.560	2.72

Table 1, continued

Event	1	2	3	4	5	6	7	8	9	10	11	12	13
Number	$\dot{z}_0/z$	$\dot{s}_0/z$	$z_0/g$	$z_0$	$\dot{z}_0$	$\dot{s}_0$	g	$\dot{s}_0/g$	$\dot{z}_0/g$	$(\dot{z}/\dot{x})_t$	Pr Err	$\overline{RT}_c$	$\overline{Conf}$
15	-.03	.50	2	72	-2.16	36	36	1.00	-.06	-.06	.301	3.128	2.40
16	-.03	.50	4	72	-2.16	36	18	2.00	-.12	-.06	.287	3.059	2.40
17	-.03	1.00	2	72	-2.16	72	36	2.00	-.06	-.03	.458	3.763	2.26
18	-.03	1.00	4	72	-2.16	72	18	4.00	-.12	-.03	.412	3.453	2.29
19	-.06	.25	2	72	-4.32	18	36	.50	-.12	-.24	.088	1.751	2.94
20	-.06	.25	4	72	-4.32	18	18	1.00	-.24	-.24	.083	1.727	2.96
21	-.06	.50	2	72	-4.32	36	36	1.00	-.12	-.12	.102	2.265	2.88
22	-.06	.50	4	72	-4.32	36	18	2.00	-.24	-.12	.060	2.082	2.87
23	-.06	1.00	2	72	-4.32	72	36	2.00	-.12	-.06	.116	2.320	2.75
24	-.06	1.00	4	72	-4.32	72	18	4.00	-.24	-.06	.116	2.500	2.73

<sup>a</sup>Variables1.  $\dot{z}_0/z$  = fractional loss in altitude (pr/sec).2.  $\dot{s}_0/z$  = global optical flow rate (h/sec).3.  $z_0/g$  = global optical texture density (g/h)4.  $z_0$  = initial altitude (m).

Table 1, continued

5.  $\dot{z}_0$  = initial descent rate (m/sec).
6.  $\dot{s}_0$  = initial path speed (m/sec).
7.  $g$  = ground texture size (m).
8.  $\dot{s}_0/g$  = path speed scaled in ground units (g/sec), i.e., approximately equal to edge rate  $(\dot{x}_0/g)$ , where  $\dot{x}_0$  = initial forward velocity or ground speed.
9.  $\dot{z}_0/g$  = descent rate scaled in ground units (g/sec), i.e., global optical texture density change.
10.  $(\dot{z}/\dot{x})_t$  = path slope (pr).
11. Pr Err = proportion error.
12.  $\overline{RT}_c$  = mean reaction time (correct only).
13.  $\overline{Conf}$  = mean confidence rating.

Note: A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event, while a subscript of  $t$  indicates the value of a variable at any time during the event. The performance means are pooled over events with flow rate constant and with flow rate accelerating, since the two conditions did not differ significantly.

1.125 m in height. The observer was seated in a stationary Singer-Link GAT-1 simulator, 2.43 m in front of the screen, with his viewpoint at the level of the simulated horizon, 1.96 m above the floor. The events represented level or descending self motion over a flat ground surface consisting of a rectilinear island covered with square texture blocks of four colors, as viewed through a window 34.2 deg wide by 26 deg high with the horizon in the middle.

### Procedure

The observer was instructed to view each computer-generated event and to indicate as soon as he/she had decided whether the event displayed represented level flight or descent by pressing one of two buttons on a hand-held box. (See Appendix A for the complete instructions.) Both the response and reaction time were recorded by the computer. Confidence ratings, indicating the observer's certainty that the decision was correct, were made on a three-point scale and entered by the experimenter. Observers were unaware that reaction times were being recorded, and no feedback was given during the course of the experiment. Each observer was tested on three blocks of trials, each block consisting of one of the three event durations, 2, 4, or 8 sec. Blocks were counterbalanced.

### Observers

Thirty-six Ohio State University undergraduates (18 male, 18 female) served as observers. None reported any previous experience in flight simulators or in piloting actual aircraft.

### Results

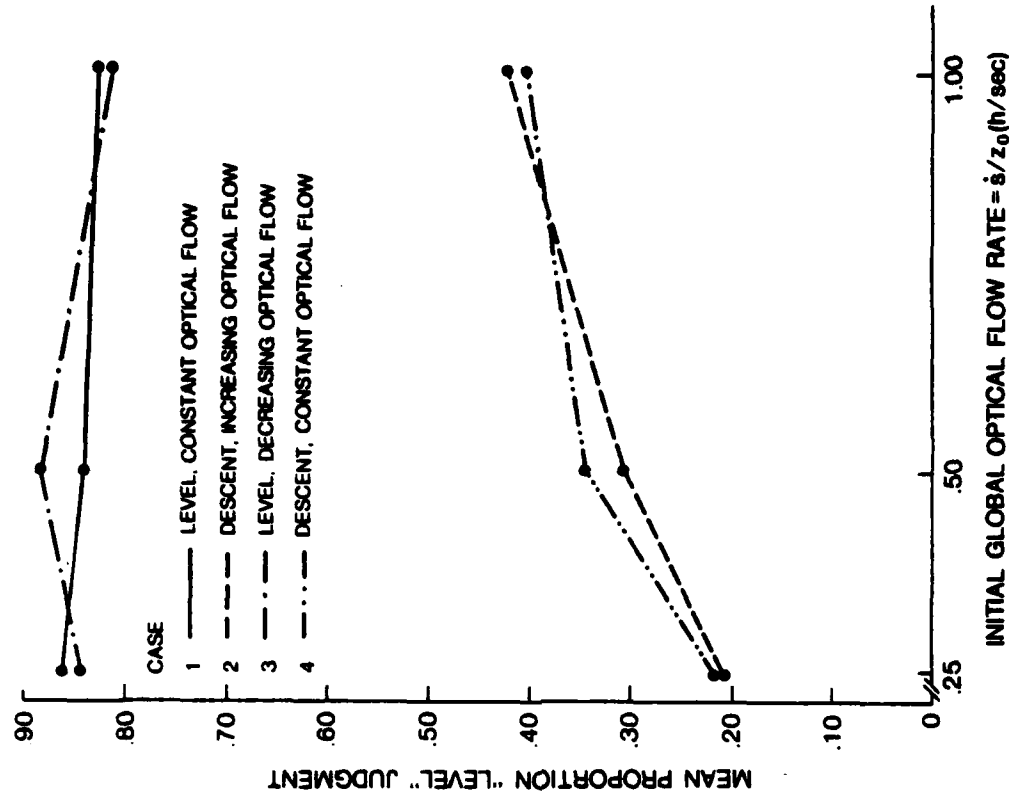
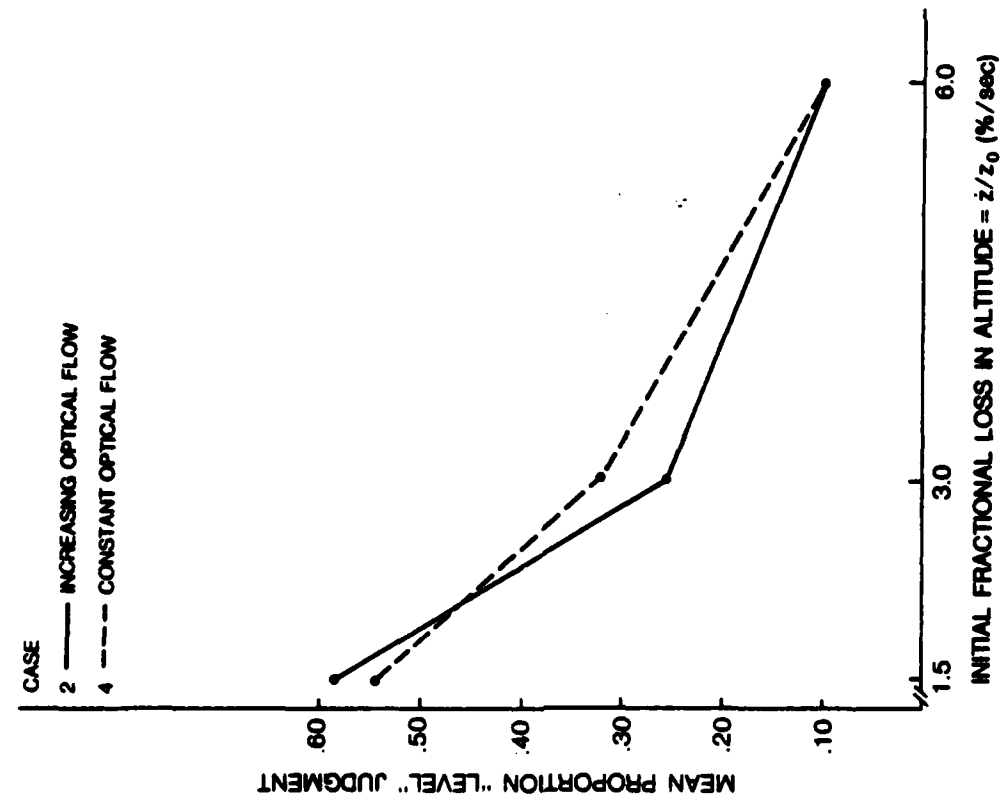
Analyses of variance were carried out using both errors and all reaction times. All effects discussed reached at least the  $p < .01$  level

of significance, and accounted for at least 1.5% of the total variance, unless otherwise indicated. (See Appendix B for the analysis of variance summary tables). Proportion error, mean correct reaction time, and mean confidence rating are given for each event in the last three columns of Table 1.

The variable which had the strongest effect on performance was fractional loss in altitude. As illustrated in Figure 2, the proportion of "level" judgments made in response to descent events decreased substantially with increases in fractional loss in altitude. Reaction times also decreased substantially with increases in fractional loss in altitude. In contrast, the presence or absence of optical flow acceleration had little effect on either performance measure.

Figure 3 shows that global optical flow rate had a negative effect on the observers' ability to detect descent, both when flow rate was held constant and when it increased. The bottom two lines of the figure index descent events which were incorrectly identified as level. Although errors increased with increase in the level of optical flow rate, again there was little effect due to eliminating flow acceleration. In a similar fashion, reaction times revealed little difference among the flow-rate conditions. Reaction times for descent events increased with increases in optical flow rate, while reaction times for level events tended to decrease with increases in optical flow rate.

Figure 4 illustrates the interaction between flow rate and fractional loss in altitude. These results indicate that the higher rates of flow used in this experiment interfered most with descent detection for events which had low rates of fractional loss. When fractional loss in altitude



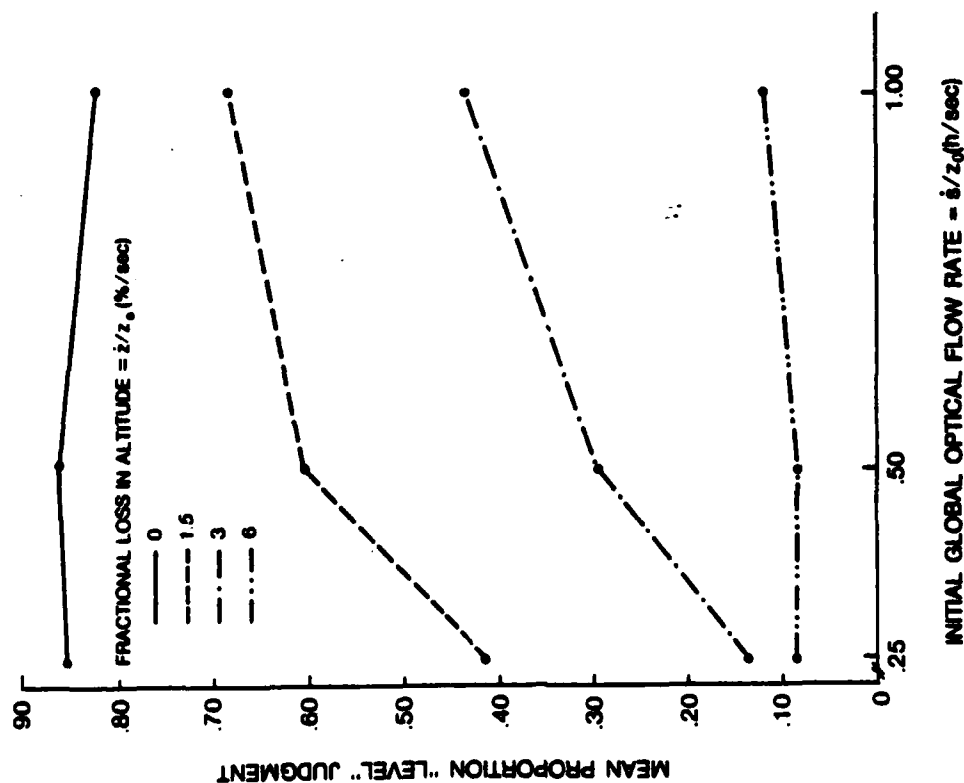


Figure 4. Mean proportion "level" judgments for the three levels of initial global optical flow rate crossed with the four levels of initial loss in altitude.

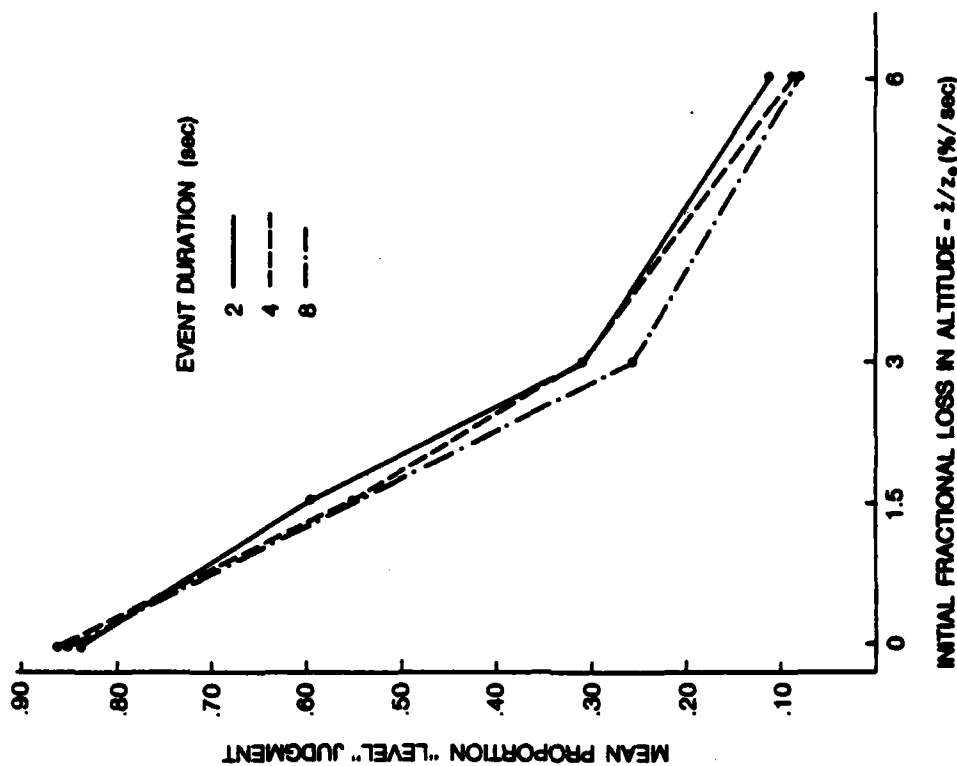


Figure 5. Mean proportion "level" judgments for the four levels of initial fractional loss in altitude crossed with the three levels of event duration.

is high, flow had almost no effect. However, when fractional loss is low and detection of descent becomes more difficult, flow rate had a considerable negative effect.

As in the preliminary experiment (Hettinger, 1981), initial optical texture density had no substantial effect on observers' performance. The two texture densities used, 2 and 4 g/h, produced only a 40 msec difference in mean reaction time and only a .5% difference in error rate.

Event duration had surprisingly little effect on accuracy, as illustrated in Figure 5. Observers were nearly equally accurate across the range of 2-, 4-, and 8-sec events. The effect, though small, was in the direction of greater accuracy with longer duration. Figure 5 also further illustrates the large effect of fractional loss in altitude on accuracy.

It is important to note that there was no evidence for any speed-accuracy tradeoff in the event-duration data. When pressed for time, observers simply picked up information more quickly with only a 3% increase in error rate as event duration was reduced from 8 sec to 2 sec.

#### Discussion

Five main points can be made concerning the significance of the results. (1) There was no substantial effect on sensitivity to loss in altitude as a result of eliminating optical flow acceleration. This finding does not justify the emphasis on flow acceleration in the literature. (2) The results indicate that at low altitudes and high speeds, where values for flow rate are highest, detection of descent may be adversely affected by the corresponding high values of optical flow rate. Exactly why high values of flow rate should interfere with

sensitivity to descent is not immediately evident from our data.

Further research will be necessary to explore this problem.

(3) Also of interest is the surprisingly small effect on performance of varying the amount of time available for viewing an event. Observers will use more time when they have it, as evidenced by their longer reaction times, but are nearly as accurate in detecting descent with short as with comparatively long event durations.

(4) Another variable which had little effect on observers' performance was texture density. This has implications for designers of flight simulation scenes, since large areas of fine texture density are expensive to generate and transform in real time.

(5) Finally, the large effect of fractional loss in altitude on sensitivity should be of interest to those studying problems of perception during low-level flight with fixed-wing aircraft, since it is at low altitudes that fractional loss takes on its highest values when descent rate is constant. For example, optical changes are much more perceptually profound given a 50-ft loss in altitude from 200 ft, as compared to the same loss in altitude from 1000 ft over the same time period. Since flow acceleration, under the conditions of this experiment, had little salience for descent detection, the remaining candidates for specifying fractional loss are optical splay increase and optical texture density decrease. These sources of information were isolated in Experiment 3.

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#### Acknowledgment

Acknowledgment is due Richard J. Jagacinski for the mathematical solution to the problem of holding global optical flow rate constant on a linear path slope.

APPENDIX A  
INSTRUCTIONS

## INSTRUCTIONS

Experimenter: First seat the observer in the simulator, then read exactly:

Welcome to the Aviation Psychology Laboratory. We are interested in investigating visual factors involved in piloting aircraft and in the design of flight simulation devices.

In today's experiment, we will be testing your ability to distinguish descent (or loss in altitude) from level flight.

The scenes you will see will differ primarily in the length of time you will have for viewing them, that is, 2, 4, or 8 seconds. In each case, your task will be to press the red button as soon as you decide the scene represents level flight, or the green button as soon as you decide the scene represents descent. It is not necessary for you to wait until the entire scene has been shown. You should respond as soon as you have made your decision about what the scene represents.

Each time you press a button to indicate your decision, we would like you to also rate your confidence in your decision. Do this by saying "1" if you guessed, "2" if you are fairly sure of your answer, and "3" if you are very sure.

After viewing 4 initial practice scenes to familiarize you with the task, you will be shown a total of 216 scenes. The entire experiment takes a little more than an hour.

Any questions?

APPENDIX B  
ANALYSIS OF VARIANCE SUMMARY TABLES

Table B-1

## Descent Events - Proportion Errors

Source	df	SS	R <sup>2</sup> (%)	F	p<F
Fractional Loss in Altitude (Z)	2	146.945	19.8	73.63	.0000
Global Optical Flow Rate (F)	2	25.847	3.5	27.46	.0000
Case (C)	1	.074	0.1	1.09	.3029
Global Optical Texture Density (D)	1	1.605	0.2	2.86	.0995
Event Duration (E)	2	1.125	0.2	2.75	.0711
ZF	4	10.133	1.4	9.88	.0000
ZC	2	1.873	0.3	9.47	.0016
FC	2	.587	0.1	3.04	.0544
ZD	2	.513	0.1	1.66	.1983
FD	2	.087	0.1	.34	.7094
CD	1	.895	0.1	10.70	.0024
ZE	4	.410	0.1	.69	.5994
FE	4	2.190	0.3	4.55	.0017
CE	2	.112	0.1	.56	.5756
DE	2	.127	0.1	.37	.6941
ZFC	4	1.523	0.2	3.91	.0048
ZFD	4	.307	0.1	.63	.6398
ZCD	2	1.538	0.2	7.69	.0010
FCD	2	.263	0.1	1.35	.2667
ZFE	8	2.04	0.3	2.28	.0226
ZCE	4	.461	0.1	1.17	.3250
FCE	4	.429	0.1	1.21	.3090
ZDE	4	1.628	0.2	4.45	.002

Table B-1, continued

Source	df	SS	R <sup>2</sup> (%)	F	p<F
FDE	4	.697	0.1	1.56	.1893
CDE	2	4.09	0.5	21.85	.0000
ZFCD	4	.649	0.1	1.95	.1054
ZFCE	8	.823	0.1	1.22	.2845
ZFDE	8	1.085	0.1	1.21	.2925
ZCDE	4	2.180	0.3	4.96	.0009
FCDE	4	5.358	0.7	11.37	.0000
ZFCDE	8	3.629	0.5	4.92	.0000
Pooled Error	3745	522.405	70.5	-	-
Total	3852	741.035	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table B-2

## Descent Events - Mean Reaction Time

Source	df	SS	R <sup>2</sup> (%)	F	p<F
Fractional Loss in Altitude (Z)	2	1449.312	11.0	118.09	.0000
Global Optical Flow Rate (F)	2	71.277	0.5	16.60	.0000
Case (C)	1	4.238	0.1	6.27	.0171
Global Optical Texture Density (D)	1	1.804	0.1	0.85	.3627
Event Duration (E)	2	4842.917	36.9	204.01	.0000
ZF	4	178.048	1.4	27.53	.0000
ZC	2	1.309	0.1	0.43	.6541
FC	2	20.561	0.2	10.10	.0001
ZD	2	2.841	0.1	1.20	.3081
FD	2	3.088	0.1	1.05	.3567
CD	1	2.228	0.1	3.40	.0738
ZE	4	350.947	2.7	42.93	.0000
FE	4	48.246	0.4	9.91	.0000
CE	2	2.568	0.1	1.53	.2246
DE	2	1.909	0.1	0.52	.5971
ZFC	4	15.826	0.1	2.88	.0248
ZFD	4	14.091	0.1	3.04	.0195
ZCD	2	5.935	0.1	2.89	.0778
FCD	2	6.190	0.1	3.19	.0470
ZFE	8	71.484	0.5	6.30	.0000
ZCE	2	13.603	0.1	2.61	.0383
FCE	4	11.312	0.1	3.26	.0138
ZDE	4	4.485	0.1	0.85	.4556

Table B-2, continued

Source	df	SS	R <sup>2</sup> (%)	F	p<F
FDE	4	7.101	0.1	1.39	.2535
CDE	2	2.422	0.1	0.78	.4614
ZFCD	4	30.929	0.2	6.80	.0000
ZFCE	8	14.142	0.1	1.27	.2584
ZFDE	8	10.024	0.1	1.25	.2698
ZCDE	4	2.705	0.1	0.68	.6051
FCDE	4	13.361	0.1	2.64	.0364
ZFCDE	8	50.975	0.4	5.53	.0000
Pooled error	3745	5886.443	44.8	-	-
Total	3852	13127.907	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

EXPERIMENT 3

## THE ISOLATION OF OPTICAL INFORMATION AND ITS METRICS FOR THE DETECTION OF DESCENT

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### ABSTRACT

Two experiments factorially contrasted eyeheight-scaled and ground-texture-unit-scaled metrics for descent detection. A third factor, texture type, was also introduced to isolate several sources of information. Use of square, vertical or horizontal texture under conditions of constant fractional loss in altitude and of accelerated fractional loss allowed an analysis of the relative importance of increase in optical (perspectival) splay, decrease in optical density, and optical acceleration as sources of information for descent. Observers were required to make "descent" or "level" judgments based on a 15-sec computer generated event. Analysis of errors and response latencies indicated that the eyeheight metric was more functionally relevant than the ground-texture-unit metric, and that the texture-type variable produced superior performance for vertical texture. Horizontal texture, which eliminates splay, produced very little information as indicated by severely impaired performance in that condition. The results suggest that optical splay change is a more salient source of information for descent than either optical acceleration or decrease in optical density.

### INTRODUCTION

Mathematical and theoretical formulations of the optical information available and useful in detecting changes in speed and altitude have assumed an eyeheight metric (Gibson, Olum, & Rosenblatt, 1955; Carel, 1961; Lee, 1974,

1976). An eyeheight is defined as the altitude ( $z$ ) of the observer's eye above the ground. Warren (1982) noted that path speed scaled in eyeheights (global optical flow rate) has a phenomenal correlate whereby the higher we are above the ground, the slower we appear to be moving.

Langewiesche (1944), on the other hand, proposed that pilots calibrate self-to-surface distance in arbitrary metrics, e.g., meters, feet, or miles. Similarly, Harker and Jones (1980) suggested that pilots use a ground metric to establish distances and vertical extents either directly or in conjunction with other elements of the terrain to establish their altitude. Presumably, changes in distances would also be calibrated in arbitrary or ground metrics.

Ground-unit scaling of velocity is also optically available. For example, as one moves forward at a constant velocity, stochastically regular ground texture is occluded by any surface which blocks the field of view (e.g., eye socket, windscreen, wing edge) at a constant rate in edges per second, irrespective of altitude. There is, however, no empirical support that texture-scaled information is being used.

In order to factorially contrast eyeheight-scaled and ground-unit-scaled metrics, change in speed during level flight cannot be used because both scales will produce identical results. Both metrics are constant during an event and when they differ it is only by a scale factor. Change in altitude, however, allows an appropriate comparison, because eyeheight can be varied while the ground unit is held constant. Nevertheless, as Warren and Owen (1981) have shown, linkages among optical variables constrain experimental designs developed to isolate potential sources of information. A simple factorial crossing will not allow a test of the two proposed metrics under exactly the same conditions. But before an

illustrative example of this problem is provided, a brief discussion of functional optical invariants is in order.

Following Owen, Warren, Jensen, Mangold, and Hettinger (1981) and Owen, Warren, and Mangold (1981), an optical variable is functional if variation in this variable covaries with performance in a task. Furthermore, the same higher-order ratio produced from different levels of environmental variables (an invariant) should result in a constant level of performance. An invariant can exist over a transformation within an event and also between events whose absolute values differ (Warren & Owen, 1981).

In our example, if descent rate ( $\dot{z}$ ) is constant along a linear path ( $\dot{z}/\dot{x}=k$ ), descent rate scaled in ground units ( $\dot{z}/g$ ) is a within-event invariant, since both  $\dot{z}$  and  $g$  are constant throughout the event. But descent rate scaled in eyeheights ( $\dot{z}/z$ ) varies because  $z$  is varying while  $\dot{z}$  is constant. An example of this difference can be seen in Figure 1 of Experiment 1 (this report).

If, however, descent along a linear path occurs at an exponentially decreasing rate which holds optical flow rate constant,  $\dot{z}/z$  is a within-event invariant, since  $\dot{z}$  and  $z$  must decrease at the same rate to remain on a linear path. Descent rate scaled in ground units ( $\dot{z}/g$ ) does, however, vary during the event since  $\dot{z}$  is decreasing while  $g$  is constant. As a result,  $\dot{z}/g$  is neither a within-event nor a between-event invariant. Thus its status as a functional optical invariant cannot be assessed under these conditions, and a set of potentially diverging operations is needed to perform the necessary evaluation.

If a constant descent rate is used, it can be determined whether  $\dot{z}/g$  is a within-event functional invariant. If so, performance (i.e., error rate, reaction time) should be the same regardless of the level of  $\dot{z}/z$ . In the same set of trials it can be determined whether  $\dot{z}/z$  is a between-event functional invariant over

different levels of  $\dot{z}/g$ . Similarly, by using exponentially decreasing descent rates, it can be determined if  $\dot{z}/z$  is a within-event functional invariant. If so, performance should be constant over differing levels of  $\dot{z}/g$ . While this manipulation necessarily replicates conditions from Hettinger's (1981) experiment, a second problem is addressed simultaneously.

Hettinger (1981) noted that fractional descent rate ( $\dot{z}/z$ ) accounted for more variance in performance than any other variable and concluded that this was probably due to the fact that fractional descent rate is specified by the relative rate of change in optical density and change in perspectival splay angle. Splay angle,  $\theta$ , is defined as follows:

$$\tan \theta = \frac{g_y}{z} \quad (1)$$

(where  $g_y$  = the lateral dimension of a ground texture unit), i.e.,

$$\theta = \arctan (g_y/z) \quad (2)$$

Change in splay angle is defined as:

$$\dot{\theta} = \left(\frac{\dot{z}}{z}\right) \cos \theta \sin \theta \quad (3)$$

Global optical density ( $z/g$ ) is defined as the number of ground texture elements spanned by one eyeheight distance, and is thus expressed in ground units per eyeheight. Change in optical density ( $\dot{z}/g$ ) is descent rate scaled in ground units.

The present study was designed to examine the informational value of splay angle change by introducing three types of surface texture, square, vertical, and horizontal, which were factorially crossed with  $\dot{z}/z$  and  $\dot{z}/g$  conditions. Vertical texture consisted of equal widths of texture extending from directly below the

point of observation to the horizon, parallel to the direction of travel. Horizontal texture consisted of equal lengths of texture, parallel to the horizon and perpendicular to the direction of travel. Square texture consisted of the overlay of the two former texture types, creating a "checkerboard" surface of squares equal in size. Examples of each type are shown in Figure 1.

Movement over vertical texture eliminates both edge rate and flow rate information for forward velocity, and provides only optical splay information. Horizontal texture eliminates splay yet provides optical expansion and edge rate information while square texture provides the combination of information specified by both vertical and horizontal texture separately.

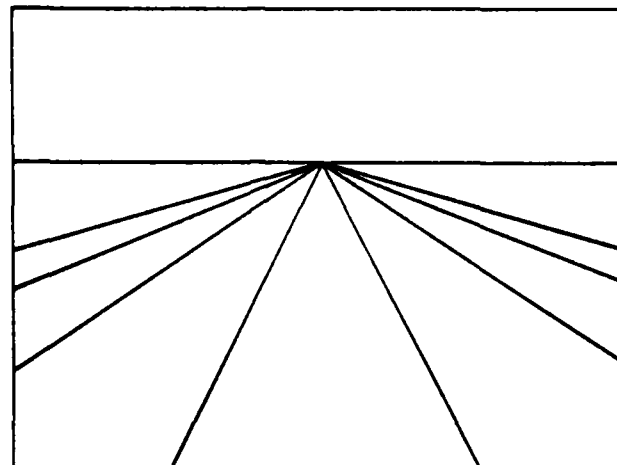
## METHOD

### Apparatus

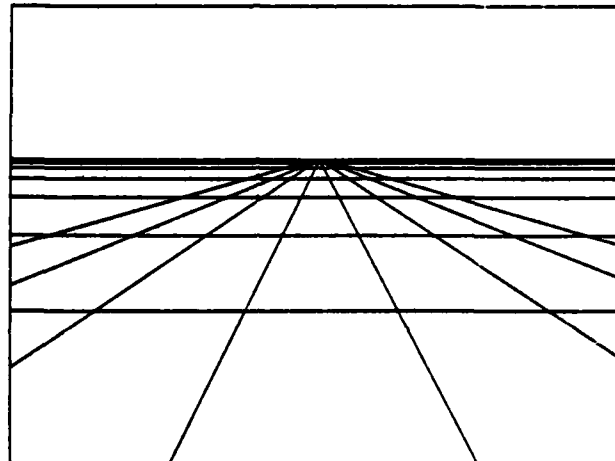
The simulated flight events were generated by a PDP 11/34 computer and a special-purpose scene generator, and displayed via a Sony model KP-7200 video projection unit having a screen 1.5 m wide and 1.125 m in height. The observer was seated on an elevated chair, 2.43 m in front of the screen, with his viewpoint at the level of the simulated horizon (1.956 m above the floor). The observer responded by pressing one of two buttons on a hand-held box. Both the response and reaction time were recorded by the computer.

### Scenes

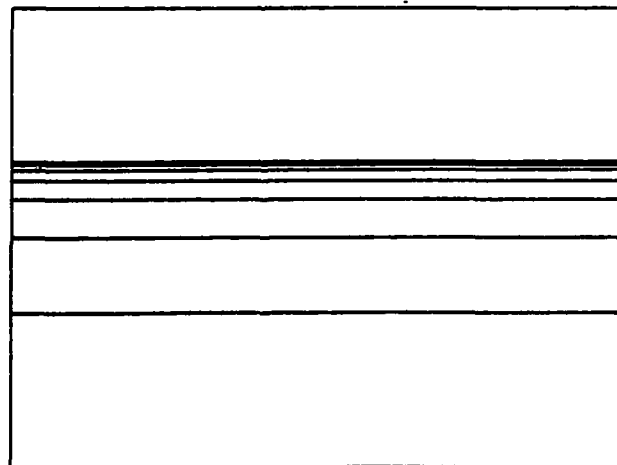
All scenes depicted a flat, rectilinearly textured plain viewed from an initial altitude of 72 m through a window 34.2 deg wide by 26 deg high with the horizon in the middle. Texture was of three types: squares, horizontal strips only, and vertical strips only. Texture size varied by a factor of 1.75, i.e., 23.50 m, 41.14 m, 72.00 m, 126.00 m, and 220.50 m. Texture colors were green, brown, yellow, and red-brown, and the sky a pale blue.



VERTICAL TEXTURE



SQUARE TEXTURE



HORIZONTAL TEXTURE

Figure 1. A schematic representation of the three texture types: vertical texture (top), square texture (center), and horizontal texture (bottom).

All events lasted 15 sec, consisting of 5 sec of level flight followed by 10 sec of either continued level or descending flight.

### Design

Three levels of eyeheight-scaled loss in altitude ( $\dot{z}/z = .020, .035, \text{ and } .061$  h/sec) were crossed with three levels of ground-unit-scaled loss in altitude ( $\dot{z}/g = .020, .035, .061$  g/sec). These nine combinations were further crossed with two levels of a third factor, a within-event constant ratio, (i.e., either  $\dot{z}/z = k$  or  $\dot{z}/g = k$ ). Finally, the three factors were fully crossed with the three levels of texture type (i.e., square, vertical, and horizontal textures). See Table 1 for an inventory of displayed events.

The resulting 54 descent trials were balanced by the same number of level trials, which matched the respective descent trials either in path speed or flow rate. Each level of this between-observers factor was presented to half (i.e., 25) of the 50 subjects.

### Procedure

A verbal "ready" signal, given by the experimenter, instructed the observer to turn full attention to the screen. The initial 5 sec of level flight was separated from the 10 sec "test" segment by an acoustic "beep". During this latter segment, the observer was to press either the "descent" or the "level" button and to indicate verbally his confidence in his choice ("1" - a guess, "2" - fairly certain, and "3" - very certain) as soon as he had made his decision. Reaction time was surreptitiously recorded, and confidence ratings were keyed in by the experimenter. No performance feedback was provided during the testing. (See Appendix A for complete instructions).

The 108 test trials were alternately presented in one of two random sequences, preceded by six practice trials, with an inter-trial interval of

Table 1  
Inventory of Displayed Events and Mean Performance

Variables <sup>a</sup>									
	1	2	3	4	5	6	7	8	9
Event No.	$\frac{\dot{z}_0}{g}$	$\frac{\dot{z}_{10}}{g}$	$\frac{\dot{z}_0}{z_0}$	$\frac{\dot{z}_{10}}{z_{10}}$	$\frac{\dot{s}_0}{z_0}$	$\frac{\dot{s}_{10}}{z_{10}}$	$\left(\frac{\dot{s}_0}{z_0}\right)\left(\frac{\dot{z}_0}{z_0}\right)$	$\left(\frac{\dot{s}_{10}}{z_{10}}\right)\left(\frac{\dot{z}_{10}}{z_{10}}\right)$	$\left(\frac{\dot{z}_0}{\dot{x}_t}\right)$
1	.020	.020	.020	.025	.278	.347	.006	.009	.072
2	.020	.020	.035	.054	.278	.427	.010	.023	.127
3	.020	.020	.061	.155	.278	.614	.017	.095	.224
4	.035	.035	.020	.025	.486	.608	.010	.015	.041
5	.035	.035	.035	.054	.486	.748	.017	.040	.072
6	.035	.035	.061	.155	.486	1.241	.030	.192	.127
7	.061	.061	.020	.025	.851	1.063	.017	.027	.024
8	.061	.061	.035	.054	.851	1.309	.030	.071	.041
9	.061	.061	.061	.155	.851	2.172	.052	.337	.072
10	.020	.016	.020	.020	.278	.278	.000	.000	.072
11	.020	.014	.035	.035	.278	.278	.000	.000	.127
12	.020	.011	.061	.061	.278	.278	.000	.000	.224
13	.035	.029	.020	.020	.486	.486	.000	.000	.041
14	.035	.026	.035	.035	.486	.486	.000	.000	.072
15	.035	.019	.061	.061	.486	.486	.000	.000	.127
16	.061	.050	.020	.020	.851	.851	.000	.000	.024
17	.061	.043	.035	.035	.851	.851	.000	.000	.041
18	.061	.033	.061	.061	.851	.851	.000	.000	.072

Table 1, continued

10	11	12	13	14	15	16	17	18	19	Event
g	$\dot{s}_0$	$\dot{s}_{10}$	$z_0$	$z_{10}$	$\dot{z}_0$	$\dot{z}_{10}$	% ERR	$\overline{RT}_c$	$\overline{Conf}$	No.
72.00	20.00	20.00	72.0	57.6	1.44	1.44	40.00	5.285	4.03	1
126.00	20.00	20.00	72.0	46.8	2.52	2.52	14.67	4.824	5.08	2
220.50	20.00	20.00	72.0	28.2	4.38	4.38	4.00	3.463	5.67	3
41.14	35.00	35.00	72.0	57.6	1.44	1.44	50.00	5.827	3.63	4
72.00	35.00	35.00	72.0	46.8	2.52	2.52	20.00	4.342	4.89	5
126.00	35.00	35.00	72.0	28.2	4.38	4.38	9.33	3.362	5.37	6
23.50	61.25	61.25	72.0	57.6	1.44	1.44	55.33	5.573	3.35	7
41.14	61.25	61.25	72.0	46.8	2.52	2.52	33.33	4.802	4.41	8
72.00	61.25	61.25	72.0	28.2	4.38	4.38	9.33	4.035	5.32	9
72.00	20.00	16.40	72.0	59.0	1.44	1.18	29.33	3.955	4.54	10
126.00	20.00	14.10	72.0	50.8	2.52	1.78	6.00	3.435	5.47	11
220.50	20.00	10.90	72.0	39.3	4.38	2.40	4.00	2.930	5.71	12
41.14	35.00	28.70	72.0	59.0	1.44	1.18	34.67	4.751	4.29	13
72.00	35.00	24.70	72.0	50.8	2.52	1.78	8.67	3.851	5.35	14
126.00	35.00	19.10	72.0	39.3	4.38	2.40	2.00	2.351	5.81	15
23.50	61.25	51.20	72.0	59.0	1.44	1.18	33.00	4.982	4.31	16
41.14	61.25	43.20	72.0	50.8	2.52	1.78	17.33	3.807	5.05	17
72.00	61.25	33.40	72.0	39.3	4.38	2.40	4.00	2.812	5.67	18

Table 1, continued

<sup>a</sup>Variables

1.  $\dot{z}_0/g$  = Initial descent rate scaled in ground units (g/sec).
2.  $\dot{z}_{10}/g$  = Final descent rate scaled in ground units (g/sec).
3.  $\dot{z}_0/z_0$  = Initial descent rate scaled in eyeheights (h/sec).
4.  $\dot{z}_{10}/z_{10}$  = Final descent rate scaled in eyeheights (h/sec).
5.  $\dot{s}_0/z_0$  = Initial global optical flow rate (h/sec).
6.  $\dot{s}_{10}/z_{10}$  = Final global optical flow rate (h/sec).
7.  $(\dot{s}_0/z_0)(\dot{z}_0/z_0)$  = Initial global optical flow acceleration (h/sec<sup>2</sup>).
8.  $(\dot{s}_{10}/z_{10})(\dot{z}_{10}/z_{10})$  = Final global optical flow acceleration (h/sec<sup>2</sup>).
9.  $(\dot{z}/\dot{x})_t$  = Path slope (pr).
10.  $g$  = Ground texture size (m).
11.  $\dot{s}_0$  = Initial path speed (m/sec).
12.  $\dot{s}_{10}$  = Final path speed (m/sec).
13.  $z_0$  = Initial altitude (m).
14.  $z_{10}$  = Final altitude (m).
15.  $\dot{z}_0$  = Initial descent rate (m/sec).
16.  $\dot{z}_{10}$  = Final descent rate (m/sec).
17. % Err = Percent error.
18.  $\overline{RT}_c$  = Mean correct reaction time (sec).
19.  $\overline{Conf}$  = Mean confidence rating converted to a 6-point scale.

Note: A dot over a symbol indicates a derivative with respect to time.

A subscript of zero indicates the value of a variable at the initiation of an event; 10, the value at the end of an event; and t, the value at any time during an event. The 5-sec preview is excluded in all cases.

approximately 10 sec. The entire procedure, with instructions and debriefing, lasted approximately 50 min.

### Observers

Fifty undergraduate students (27 male, 23 female) served as observers in partial fulfillment of an introductory psychology course requirement. All observers claimed no prior experience as pilots or in flight simulators, and all reported normal vision.

## RESULTS

A repeated-measures analysis of variance showed that all the main effects, the texture factor, the eyeheight metric, and the ground unit metric, reached the  $p < .0001$  level of significance. However, statistical significance in the conventional sense is easily obtained in this type of experiment due to the large number of observations. An examination of the amount of variance accounted for by each factor showed that texture type accounted for 12.1% of the variance in error rate and 6.5% in reaction time. The eyeheight metric accounted for 12.9% of the variance in error rate and 10.2% in reaction time, whereas the ground-unit metric accounted for only 0.8% of the variance in error rate and 0.2% in reaction time. See Table 2 for mean performance scores for each event within each texture type.

Figures 2 and 3 illustrate the overall superiority of performance in the vertical texture condition, compared with the square and horizontal texture, with poorest performance in the horizontal texture condition. Within the vertical condition, which contained no information about forward velocity, it can be seen that greater fractional loss in altitude ( $\dot{z}/z$ ) resulted in better performance (Figure 2). In contrast, increase in the levels of loss of altitude scaled in ground units ( $\dot{z}/g$ ) did not affect performance (Figure 3).

Table 2

## Mean Performance for the Three Texture Types

Event	Percent Error			Mean Correct RT			Mean Conf. Rating		
	1	2	3	4	5	6	7	8	9
No.	Vert.	Square	Horiz.	Vert.	Square	Horiz.	Vert.	Square	Horiz.
1	16.00	20.00	84.00	4.942	5.472	6.174	5.04	4.68	2.38
2	12.00	6.00	26.00	5.202	4.069	5.332	5.24	5.52	4.48
3	8.00	0.00	4.00	4.244	3.292	2.888	5.46	5.82	5.72
4	24.00	44.00	82.00	5.390	6.112	6.733	4.52	3.90	2.48
5	12.00	4.00	44.00	4.218	3.523	6.000	5.28	5.72	3.66
6	2.00	0.00	26.00	2.929	2.508	5.089	5.78	5.96	4.38
7	38.00	66.00	62.00	4.107	6.706	7.026	4.24	2.90	2.92
8	2.00	28.00	70.00	4.457	4.652	6.289	5.62	4.64	2.96
9	0.00	2.00	26.00	3.822	2.770	5.997	5.76	5.84	4.36
10	18.00	8.00	62.00	4.123	3.187	5.454	5.04	5.46	3.12
11	6.00	0.00	12.00	3.447	2.446	4.523	5.52	5.90	5.00
12	2.00	2.00	8.00	2.909	2.696	3.207	5.76	5.86	5.50
13	12.00	20.00	72.00	4.235	4.941	5.855	5.26	4.82	2.78
14	6.00	2.00	18.00	3.819	2.773	5.177	5.54	5.72	4.78
15	2.00	0.00	4.00	2.178	1.987	2.907	5.88	5.92	5.64
16	4.00	24.00	72.00	3.735	5.997	6.622	5.64	4.50	2.80
17	2.00	0.00	50.00	2.804	3.455	6.597	5.84	5.78	3.54
18	0.00	0.00	12.00	2.400	1.972	4.226	5.88	5.98	5.14

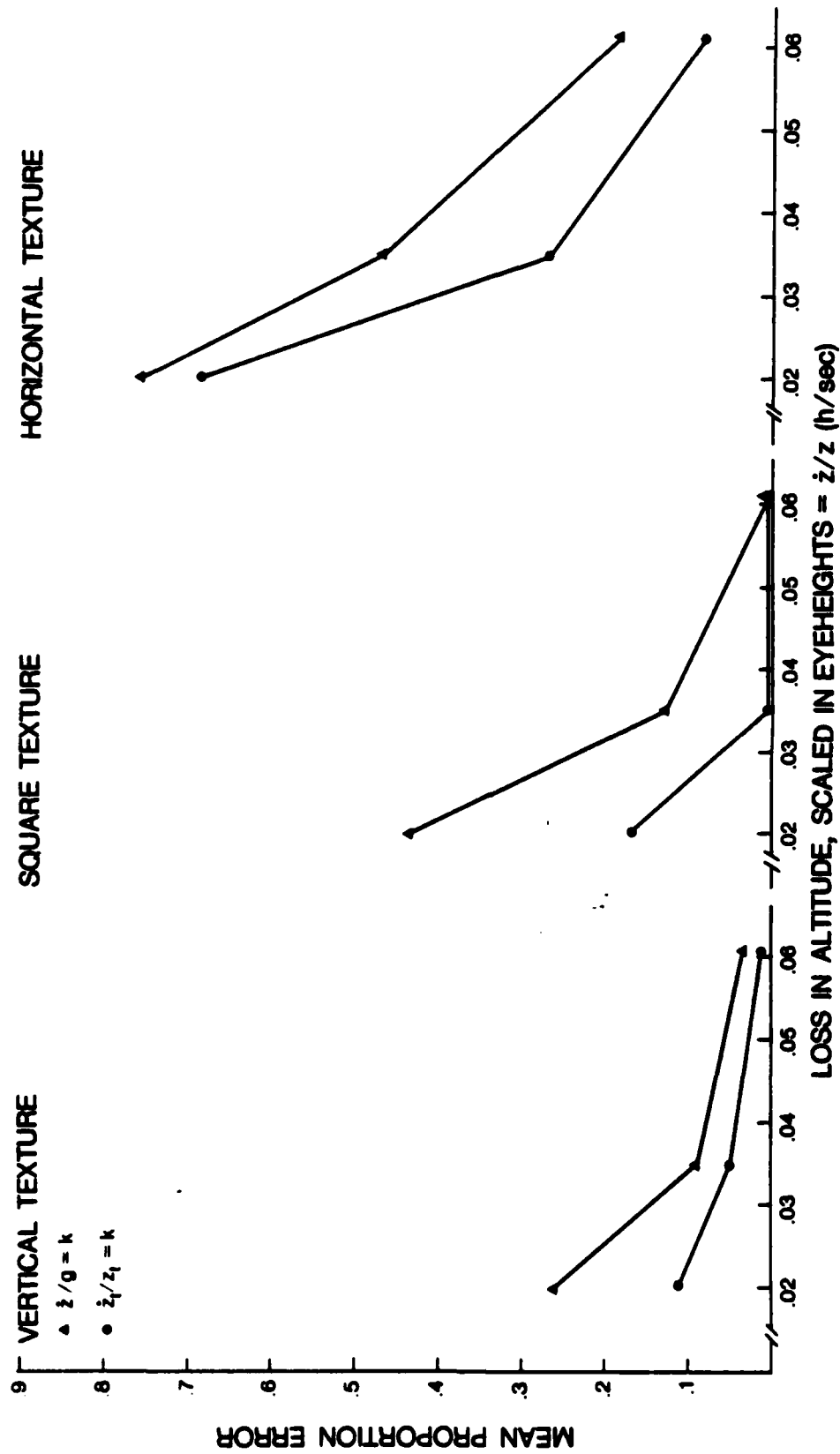


Figure 2. Proportion error for the three levels of eyeheight-scaled loss in altitude over the three texture types, under conditions of constant optical flow rate ( $\dot{z}_t/z_t = k$ ) and optical flow acceleration ( $\ddot{z}_t/g = k$ ).

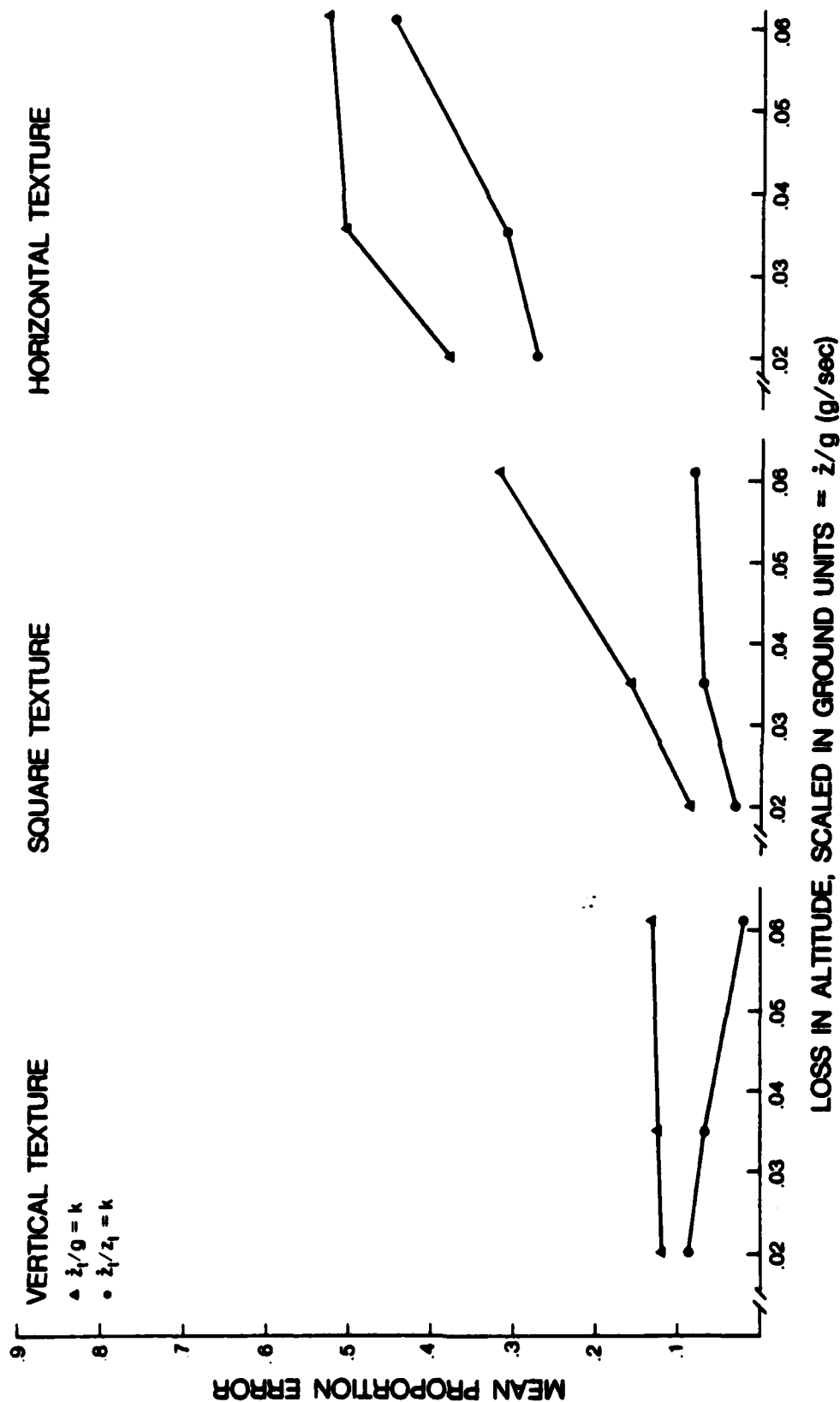


Figure 3. Proportion error for the three levels of ground-unit-scaled loss in altitude over the three texture types, under conditions of constant optical flow rate ( $\dot{z}_t/z_t = k$ ) and optical flow acceleration ( $\ddot{z}_t/g = k$ ).

A fourth significant factor, constant optical flow vs. accelerating optical flow, accounted for 1.7% of the variance in error rate and 2.7% in reaction time. At every level of fractional loss, optical flow acceleration resulted in performance inferior to constant optical flow.

#### DISCUSSION

The results suggest that the eyeheight metric is much more functionally pertinent in specifying loss in altitude than is the ground-unit metric. While both metrics were found to be significant in terms of analysis of variance, the percent of variance accounted for by the eyeheight metric was sixteen times greater than that of the ground-unit metric in the error measure, and fifty times greater in the reaction time measure.

The usefulness of change in splay information was demonstrated by superior performance when splay information was available (vertical and square texture) than when it was absent (horizontal texture).

The consistently inferior performance under conditions of accelerating optical flow is potentially significant for future studies. The finding that optical flow acceleration did not aid in the detection of descent, and in fact hindered, is counter-intuitive. This interference tends to increase with higher flow rates. Curiously, this effect did not appear in the Hettinger, Owen, and Warren study (see this report), in which similar events, excluding the five-sec preview period, were presented. This discrepancy demands further examination.

In conclusion, this study demonstrated the validity of the methodology for the isolation of optical variables, their metrics, and tests of their usefulness.

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APPENDIX A  
INSTRUCTIONS

## INSTRUCTIONS

Experimenter: Seat the subject and read exactly:

In this experiment we are interested in investigating your sensitivity to loss in altitude. We want to find out how well you can visually detect descent, in the absence of motion or kinesthetic cues, for example, change in gravitational pull in a descending elevator.

You will be shown computer-generated scenes on the screen which represent travel in an airplane over open, flat fields. Your flightpath will be level in some scenes, and descending in others. Your task will be to press the red button marked "L" if you believe the scene represents level flight, or the green button, "D", if you detect descent.

The size of the simulated fields will vary from scene to scene as will the texture type. For example, the fields may either be squares, vertical strips only, or horizontal strips only. Likewise, the simulated speed of travel will vary. No matter the size or type of the textured fields, or how fast or slow you travel, you should base your judgements only on whether you see descent or not.

Sometimes you will see a shimmer or flicker of the fields along the horizon. Please ignore this effect. It is due to limitations in our equipment.

The specific procedure is as follows:

1. Before the beginning of each scene, I will say "ready". Turn your full attention to the screen.

2. A scene beginning with 5 seconds of level travel will appear. After the 5 seconds, you will hear a beep. After this signal, the scene may continue level or begin to descend. Each scene will last for 10 seconds after the signal.
3. As soon after the beep as you can distinguish which type of motion is represented, press the button corresponding to your choice ("L" or "D"). You do not have to wait until the end of the scene to press the button but a judgement must be made for each scene. Please make sure that you press the button only once per scene, and do not press any button in between the scenes at all.
4. After you press the button, rate your confidence in your accuracy by saying "one" if you guessed, "two" if you are fairly certain, or "three" if you are very certain of your answer.
5. Prior to the actual experiment, you will be shown 6 practice scenes, to be sure you fully understand the procedure. Then you will be shown a total of 108 scenes, with a short rest break in the middle.

Do you have any questions?

Experimenter: Describe the practice scenes:

Scene #1 is descent over square texture.

Scene #2 is descent over vertical texture.

Scene #3 is level over horizontal texture.

Scene #4 is level over square texture.

Scene #5 is descent over vertical texture.

Scene #6 is level over vertical texture.

APPENDIX B

ANALYSIS OF VARIANCE SUMMARY TABLES

Table B-1  
Analysis of Descending Events

Source	df	SS	R <sup>2</sup> (%)	F	p<F
Proportion Errors					
Descent in eyeheights (Z)	2	57.490	12.9	177.08	.0000
Descent in ground units (G)	2	3.736	0.8	16.98	.0000
Texture type (T)	2	54.101	12.1	158.80	.0000
Flow rate constancy (K)	1	7.787	1.7	86.97	.0000
ZG	4	1.555	0.3	3.92	.0044
ZT	4	14.544	3.3	31.04	.0000
ZK	2	1.614	0.4	10.05	.0001
GT	4	3.197	0.7	7.00	.0000
GK	2	0.732	0.2	5.00	.0087
TK	2	0.501	0.1	3.13	.0481
ZGT	8	7.992	1.8	12.32	.0000
ZGK	4	.177	0.0	0.54	.7089
ZTK	4	2.268	0.5	5.49	.0003
GTK	4	1.530	0.3	4.15	.0030
ZGTK	8	3.841	0.9	5.31	.0000
Pooled error	2646	284.540	63.9	-	-
Total	2699	445.605	100.0	-	-
Mean Reaction Time					
Descent in eyeheights (Z)	2	1958.789	10.2	141.90	.0000
Descent in ground units (G)	2	29.468	0.2	4.24	.0172
Texture type (T)	2	1242.447	6.5	59.51	.0000
Flow rate constancy (K)	1	512.712	2.7	118.48	.0000

Table B-1, continued

Source	df	SS	R <sup>2</sup> (%)	F	p<F
ZG	4	93.509	0.5	6.81	.0000
ZT	4	173.626	0.9	10.72	.0000
ZK	2	16.767	0.1	3.35	.0394
GT	4	310.574	1.6	20.20	.0000
GK	2	0.222	0.0	0.05	.9476
TK	2	47.653	0.3	9.08	.0002
ZGT	8	270.774	1.4	11.55	.0000
ZGK	4	48.633	0.3	4.96	.0008
ZTK	4	75.816	0.4	6.40	.0001
GTK	4	89.810	0.5	7.93	.0000
ZGTK	8	110.242	0.6	4.14	.0001
Pooled error	2646	14159.408	74.0	-	-
Total	2699	19140.650	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table B-2

## Analysis of Descending Events, Vertical Texture Only

Source	df	SS	R <sup>2</sup> (%)	F	p>F
Proportion Error					
Descent in eyeheights (Z)	2	4.296	5.7	21.73	.0000
Descent in ground units (G)	2	.116	0.2	0.84	.4366
Flow rate constancy (K)	1	1.068	1.4	15.04	.0003
ZG	4	.424	0.6	1.70	.1510
ZK	2	.696	0.9	6.48	.0023
GK	2	.249	0.3	1.91	.1544
ZGK	4	1.518	2.0	6.15	.0001
Pooled error	882	66.980	88.9	-	-
Total	899	75.357	100.0	-	-
Mean Reaction Time					
Descent in eyeheights (Z)	2	369.794	6.2	40.15	.0000
Descent in ground units (G)	2	124.740	2.1	18.50	.0000
Flow rate constancy (K)	1	255.538	4.3	95.83	.0000
ZG	4	62.772	1.1	5.39	.0004
ZK	2	7.895	0.1	1.58	.2121
GK	2	9.041	0.2	1.73	.1835
ZGK	4	35.090	0.6	2.37	.0537
Pooled error	882	5056.893	85.4	-	-
Total	899	5921.763	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table B-3

## Analysis of Descending Events, Square Texture

Source	df	SS	R <sup>2</sup> (%)	F	p<F
Proportion Error					
Descent in eyeheights (Z)	2	14.762	14.9	55.38	.0000
Descent in ground units (G)	2	2.976	3.0	22.57	.0000
Flow rate constancy (K)	1	3.610	3.7	58.81	.0000
ZG	4	2.684	2.7	11.10	.0000
ZK	2	2.540	2.6	18.55	.0000
GK	2	1.487	1.5	11.79	.0000
ZGK	4	0.653	0.6	2.35	.0558
Pooled error	882	70.100	70.9	-	-
Total	899	98.812	100.0	-	-
Mean Reaction Time					
Descent in eyeheights (Z)	2	1171.716	20.6	115.93	.0000
Descent in ground units (G)	2	48.561	0.9	7.04	.0014
Flow rate constancy (K)	1	249.507	4.4	81.48	.0000
ZG	4	191.069	3.4	16.42	.0000
ZK	2	26.381	0.5	4.83	.0100
GK	2	28.081	0.5	6.20	.0029
ZGK	4	34.968	0.6	4.15	.0030
Pooled error	882	3940.691	69.2	-	-
Total	899	5690.974	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

Table B-4

## Analysis of Descending Events, Horizontal Texture Only

Source	df	SS	R <sup>2</sup> (%)	F	p<F
Proportion Error					
Descent in eyeheights (Z)	2	52.976	24.4	161.07	.0000
Descent in ground units (G)	2	3.842	1.8	9.45	.0002
Flow rate constancy (K)	1	3.610	1.7	30.87	.0000
ZG	4	6.438	3.0	11.61	.0000
ZK	2	0.647	0.3	1.96	.1460
GK	2	0.527	0.2	2.04	.1358
ZGK	4	1.847	0.9	3.50	.0088
Pooled error	882	147.459	67.8	-	-
Total	899	217.346	100.0	-	-
Mean Reaction Time					
Descent in eyeheights (Z)	2	590.904	9.4	55.29	.0000
Descent in ground units (G)	2	166.741	2.7	19.21	.0000
Flow rate constancy (K)	1	55.319	0.9	14.38	.0004
ZG	4	110.442	1.8	7.95	.0000
ZK	2	58.308	0.9	9.12	.0002
GK	2	52.910	0.8	9.31	.0002
ZGK	4	88.817	1.4	6.70	.0000
Pooled error	882	5161.821	82.1	-	-
Total	899	6285.262	100.0	-	-

Note: Each effect was tested using the appropriate error term given by the model.

**END**

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